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ANALYSIS OF FILM THICKNESS EFFECT IN SLOW-SPEED LIGHTLY-LOADED ELASTOHYDRODYNAMIC CONTACTS

Part II. Measurement of Film Thicknesses in Vacuum.

SOUTHWEST RESEARCH INSTITUTE

JANUARY 1976

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This report presents a summary of the second year's effort in a two-year program to study the influence of oil film thickness on bearing-lubricant life expectancy in despin mechanical assembly-type bearings operating in vacuum. Results of elastohydrodynamic film thickness measurements made by the optical interference technique in a SwRI optical tester are presented for seven oils, some of which have been employed in actual space flight hardware. These results show that the special oils formulated for vacuum

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use behave in a manner similar to ordinary straight mineral oils. Extensive experimental EHD film thickness data were obtained for DMA-type bearings operating in a vacuum and lubricated with various oils, and these results are presented and discussed. These film thickness measurements were made using a race displacement technique developed during the first year's work at SwRI. The measurements show that, in general, lubricant starvation occurs in the bearings with the result that the EHD film thicknesses are less than those predicted by the theoretical equations for flooded EHD lubrication. The results from long-term tests with DMA-type bearings operating in vacuum are also presented. Two bearing failures occurred and these failures are attributed to problems associated with lubrication of the interfaces between the retainer and the other bearing components. Examination of the bearings after test termination reveals that substantially full EHD lubrication (not flooded, but separation of bearing surfaces) at the ball-race contacts apparently prevailed for the duration of the tests.

FOREWORD

This report was prepared by Southwest Research Institute, 8500 Culebra Road, San Antonio, Texas, under Contract F33615-73-C-5123. The contract was initiated under Project No. 7343, "Aerospace Lubricants," Task No. 734303. The work was administered by the Lubricants and Tribology Branch, Nonmetallic Materials Division, Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. The project engineers were Dr. M. Rivera, Dr. W. E. Ward, and Mr. R. J. Benzing, AFML/MBT.

Acknowledgment is given to Mr. Harold Haufler of SwRI for assisting in the development of the test facilities and also for conducting the experiments and participating in the analysis of the test data.

The report is issued in two parts: Part I, Development of Film Thickness Measurement Technique, and Part II, Measurement of Film Thicknesses in Vacuum. Part I was published in December 1974; Part II is contained herein.

Part II of the report covers the period of July 1, 1974, through June 15, 1975, and was submitted by the authors in September 1975.

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SECTION I

INTRODUCTION

1. Objectives and Scope

As specified in the Statement of Work of Contract F33615-73-C-5123, the objectives of the proposed program are: (a) to determine the oil film thickness in an axially-loaded, angular-contact ball bearing under conditions typified by a despin mechanical assembly (DMA), and (b) to define the influence of oil film thickness on lubricant and bearing performance in long-life DMA systems.

In order to accomplish these objectives, the Statement of Work outlines three major tasks, as follows:

Task I — Development of an experimental technique for film thickness measurement in slow-speed, lightly-loaded elastohydrodynamic contacts.

Task II — Experimental measurements of film thickness in typical despin mechanical assembly bearings operating in a space (vacuum) environment.

Task III — Analysis of the influence of film thickness on lubricant film performance and bearing life expectancy in a space (vacuum) environment.

This report is issued in two parts: Part I, Development of Film Thickness Measurement Technique, and Part II, Measurement of Film Thicknesses in Vacuum. Part I of the report, submitted in July 1974 and published in December 1974,(1) was concerned principally with the work done under Task I, i.e., the development of a technique uniquely applicable to the measurement of the oil film thickness in angular-contact bearings, as are typically employed in DMA's. It also outlined the test plans for Tasks II and III. Part II of the report, submitted herewith, will present the results of the Tasks II and III tests, together with further analysis of the Task I results. Briefly, Task II involves film thickness measurements in typical DMA bearings in a simulated space (vacuum) environment, and Task III entails selected long-duration bearing tests in a simulated space (vacuum) environment. The objectives of Task II are to apply the basic technique developed in Task I to typical DMA bearings and to examine how the oil film thickness varies with lubricant formulations and operating conditions. The objectives of Task III are to generate experimental data relating the oil film thickness to bearing performance and to provide a realistic foundation for the development of accelerated tests for bearing life prediction.

Since this part of the report is a continuation of Part I, much of the material contained in Part I will not be repeated herein, but will be summarized or referenced for the sake of completeness.

2. Prior Accomplishments — Part I Review

Part I of this report described the experimental and analytical work performed on the development of a technique to measure the oil film thickness in an actual bearing operating in vacuum. Preliminary tests with actual bearings showed that the technique, involving the measurement of the displacement of the bearing race due to the development of elastohydrodynamic oil films at the ball-race conjunctions, was feasible. In addition to these preliminary bearing tests, extensive measurements of the elastohydrodynamic oil film thickness were made by both the displacement technique and the optical interference technique in a SwRI optical EHD tester. These measurements were made and compared using six different test oils, some of which have been employed in actual space flight hardware. These results indicated a need for further measurements and analyses, which will be reported in Section III herein.

SECTION II

TEST MATERIALS AND EQUIPMENT

1. Test Bearings

The test bearings selected for use in this program were discussed in Section II, Part I of this report. They were manufactured by the Marlin-Rockwell Company (MRC) and are typical DMA bearings, ABEC-7 grade, angular-contact ball bearings with a counterbored inner race, 100-mm bore, and a contact angle of 26° ± 1°. The surface finish of the balls in all test bearings was approximately 0.025 μm (1 μin.). However, as requested by SwRI, some bearings were to have a "standard" surface finish on the races and others were to have a race surface finish approximately twice the "standard." According to the information supplied by MRC, the "standard" race finish was approximately 0.102 μm (4 μin.) transverse (across the grinding marks), and the rougher race finish was approximately 0.204 μm (8 μin.) transverse. This roughness variation was to be employed to determine the effect of surface finish on the measured oil film thickness and on the bearing life in Tasks II and III.

Upon receipt of the test bearings from MRC, they were not disassembled, but were shipped directly to Ball Brothers Research Corporation (BBRC) for special application of the test lubricants. When the bearings were returned from BBRC to SwRI, they again were not disassembled prior to being used for testing in order to minimize the possibility of contamination. Consequently, it was not possible to check the surface roughness of the bearing races until after completion of the Task II tests and after termination of two of the Task III endurance tests.

The post-test surface roughness measurements were made on one "standard" bearing and one rough bearing, using a Talysurf surface finish measuring instrument equipped with a curved-surface attachment. These measurements showed that the inner-race surface roughness of the rough bearing was not much different from that of the standard bearing. The measurements were made using two wave "cutoff" lengths. The longer wave "cutoff" length of 0.076 cm (0.03 in.) gave an average value over a longer distance across the bearing race and consequently included an additional amount contributed by any waviness of the surface. The wave "cutoff" length of 0.025 cm (0.01 in.) was only 1/3 as long and would exclude much of the waviness, unless the frequency of waviness is extremely high. It was found that the longer wave "cutoff" length gave surface finish values about 3 to 7 times those given by the shorter wave "cutoff" length. Therefore, it is concluded that the race surfaces have an appreciable amount of waviness that contributes to the surface roughness reading when using the longer wave "cutoff" length. The values that were obtained using the two wave "cutoff" lengths along with the race surface finish values furnished by MRC are as follows:

	Bearing Inner-Race Roughness, µm (µin.)	
	Standard finish	Rough finish
SwRI 0.076 cm wave "cutoff" length	0.335 (13.20)	0.422 (16.62)
SwRI 0.025 cm wave "cutoff" length	0.087 (3.44)	0.062 (2.42)
MRC information	0.102 (4)	0.204 (8)

As seen from these data there is a significant difference in the values obtained by the two organizations. Further examination of the graphic traces obtained by both MRC and SwRI when traversing the bearing race surfaces led to the conclusion that the MRC values are probably more indicative of the true surface character. The MRC traces are more consistent and uniform and do indeed show that the amplitude of the stylus trace for the rough bearings is about twice that of the standard bearings. Consequently it was decided to accept the MRC roughness values for the purposes of the present study.

These measurements do show that surface roughness values obtained at different laboratories using different measuring instruments can vary considerably, thus making it a very controversial subject. Of course the width and length of the penetrating stylus will also influence the surface roughness information obtained. Discrepancies in measured surface roughness values at different laboratories using different measuring instruments is not new and certainly deserves further study to resolve these differences.

Based on the MRC measured data, the effect of ball-race composite surface roughness on the oil film thicknesses in EHD conjunctions in bearings, which is one of the variables to be investigated in Task II can be made in this study. Also, the three different Λ ratios (ratio of oil film thickness to ball-race composite surface roughness) will lend themselves to analysis in the Task III tests. Details of these results will be discussed in Sections IV and V herein.

2. Test Oils

Six different test oils were employed in this program, with emphasis being placed on several space-proven ones. These oils were supplied and applied to the test bearings by Ball Brothers Research Corporation (BBRC), which organization served as a subcontractor to SwRI in this program.

In addition to the six test oils, data on the elastohydrodynamic film thickness behavior of a straight mineral oil, SwRI Oil B, obtained in a previous SwRI program, (2) are cited for comparison.

The properties of the seven oils were discussed in detail in Section II, Part I of this report, and will not be repeated here.

3. Bearing Test Rig and Associated Instrumentation

A cross-section of the bearing test rig is shown in Figure 1 and a complete parts list keyed to the drawing is given in Table 1. There have been a few modifications made to the original design as presented in Section II, Part I of this report. Therefore, a revised drawing and parts list are presented herein for the sake of clarity.

Four identical bearing test rigs were fabricated; three were used for the long-duration tests in Task III and one for the short-duration tests in Task II. The test bearings (33) are mounted on a shaft (4) and axially preloaded by means of the diaphragm (7) which is deflected a selected distance by the bearing preload ring (10). Diaphragm load/deflection calibration was determined by using deadweights and a dial indicator. At a load of 890 N (200 lb) the axial deflection is 0.86 mm (0.034 in.). Rotary motion is imparted to the shaft by means of a magnetic coupling consisting of an inner magnet (22) and an outer magnet (23) which is mounted on the shaft of a variable speed DC motor (51). Motor speed is indicated by means of a magnetic pickup activated by a 60-tooth gear (not shown in Fig. 1) mounted on the motor shaft. Bearing temperatures are measured by means of 1/16-in. diameter sheathed thermocouples (32) which contact the outer ring of each bearing.

The technique employed for measuring oil film thickness in these tests consists of measuring the axial movement of the floating bearing by means of a linear variable differential transformer (LVDT). The LVDT components consist of a core (14) attached to the bearing cartridge (5) that carries the floating bearing and a winding (20) that is attached to the retainer plate (15).

For lubrication, the test bearings are initially coated with a film of oil and the bearing cages are impregnated with the same oil. Also, for some tests, impregnated reservoirs (16) are installed within the bearing chamber.

A photograph of the three long-duration test rigs used in Task III, as attached to the 1200 ℓ/s ion pump, is shown in Figure 2. Much of the instrumentation employed is also shown in the photograph. Figure 3 illustrates a closeup view of one of the test rigs. Details of the instrumentation and vacuum systems employed are given in Section II, Part I of the report.

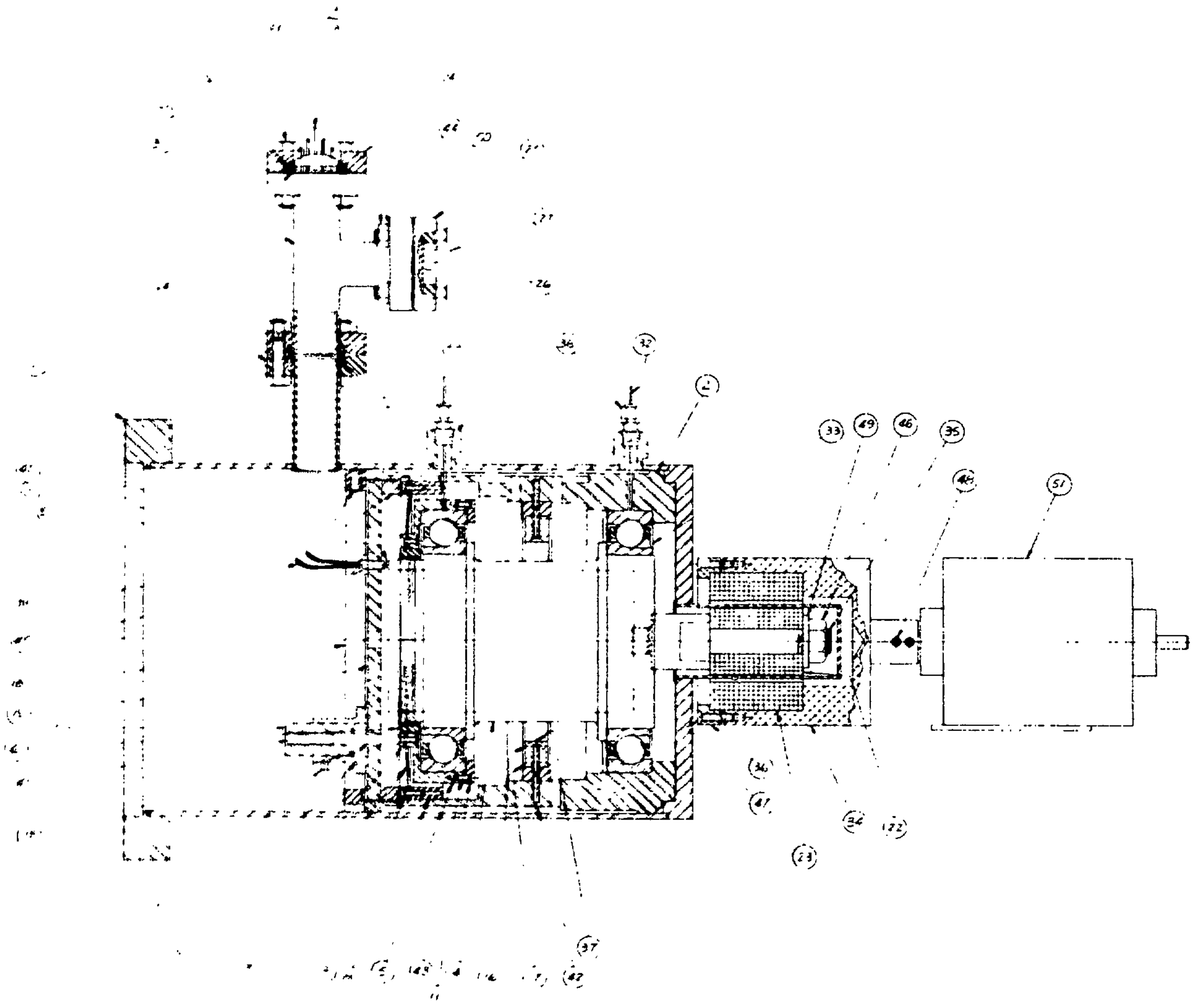
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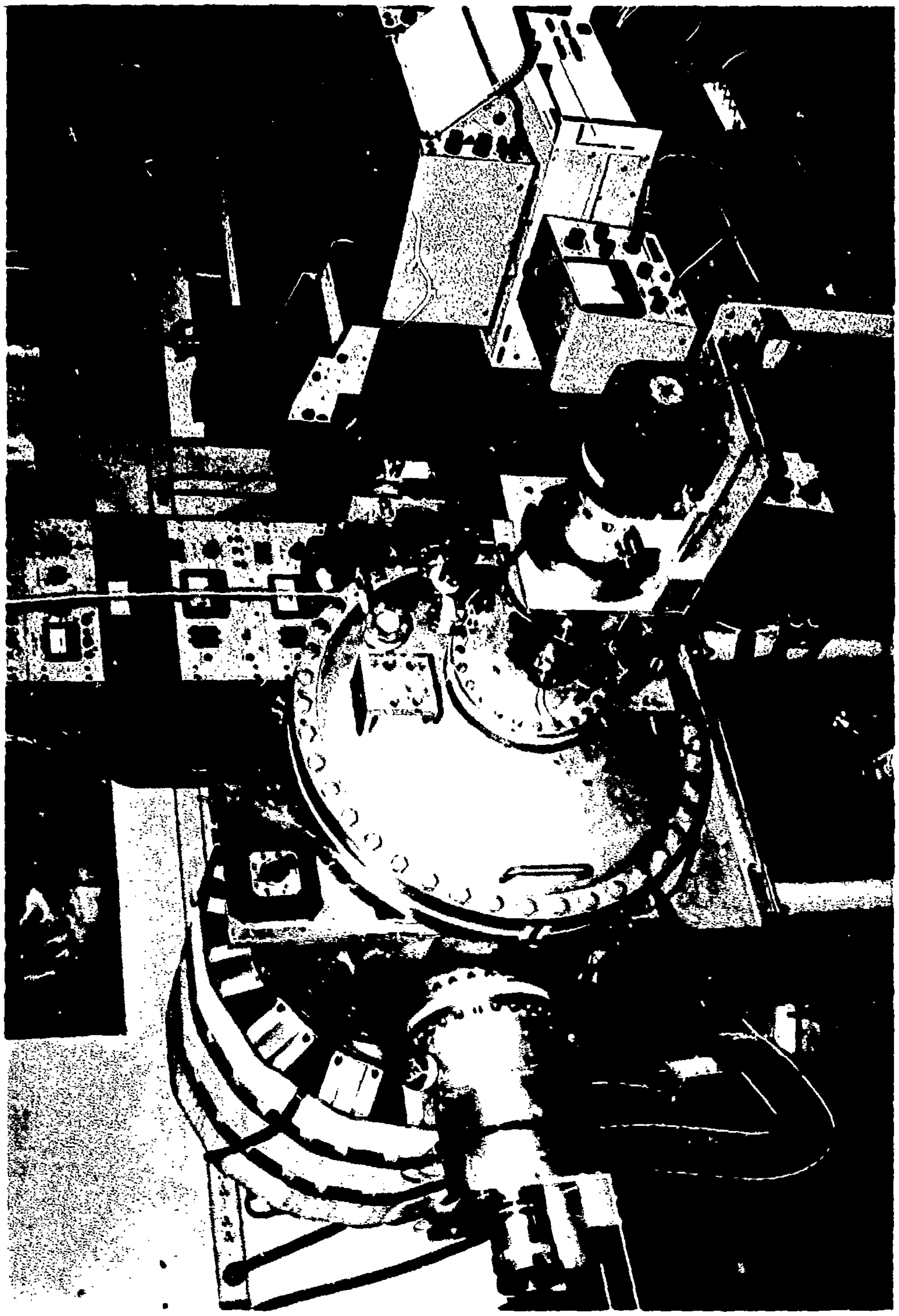
Figure 1. Bearing Test Rig

TABLE 1. BEARING TEST RIG PARTS LIST

Identifying No.	Description	No. Req'd
1	Bearing rig chamber	1
2	Inner housing	1
3	1-in. O.D. vacuum tee	1
4	Drive shaft	1
5	Bearing cartridge	1
6	Bearing locknut	1
7	Diaphragm	1
8	Diaphragm mounting ring	1
9	Diaphragm retainer ring, outer	1
10	Bearing preload ring	1
11	Bearing retainer ring	1
12	Diaphragm retainer ring, inner	1
13	Mounting rod, LVDT core	1
14	LVDT core, Hewlet-Packard 585T-050-BM	1
15	Retainer plate	1
16	Oil reservoir (90° segments)	4
17	Oil reservoir mounting ring	1
18	Assembly retainer ring	1
19	Housing, LVDT	1
20	LVDT winding, Hewlet-Packard 585DT-050-BM	1
21	6-32 x 1/2 slotted cap screw	3
22	Magnet, inner	1
23	Magnet, outer	1
24	Vacuum flange	6
25	Vacuum flange insert	4
26	Vacuum flange insert, modified	2
27	Vacuum feed through, lubricant	1
28	Vacuum feed through, electrical	1
29	Terminal header, Latronics No. 97.1735	1
30	Copper gasket, 1-in.	3
31	Magnetic pickup, Electro Products No. 3080	1
32	Thermocouple, 1/16 sheath	2
33	Test bearing	2
34	Magnet cartridge	1
35	Input shaft	1
36	Magnet lock ring	1
37	6-32 x 5/8 flat heat screw	4
38	Thermocouple compression fitting, Omega SSLK-116	2
39	Adapter, thermocouple compression fitting	2
40	1/4-20 x 1/2 socket head cap screw	3

TABLE 1. BEARING TEST RIG PARTS LIST (Cont'd)

Identifying No.	Description	No. Req'd.
41	1/4-20 x 1-1/4 hexagon head cap screw	12
42	6-32 x 3/4 flat head screw	4
43	6-32 x 3/8 flat head screw	36
44	1/4-20 hexagon nut	12
45	10-32 hexagon nut	1
46	9/16-18 hexagon nut	1
47	8-32 x 3/4 flat head screw	6
48	10-32 x 3/8 socket head set screw	2
49	9/16 flat washer	1
50	1/4 lock washer	12
51	DC drive motor, Bodine No. 280	1
52	Ferromagnetic pin	1



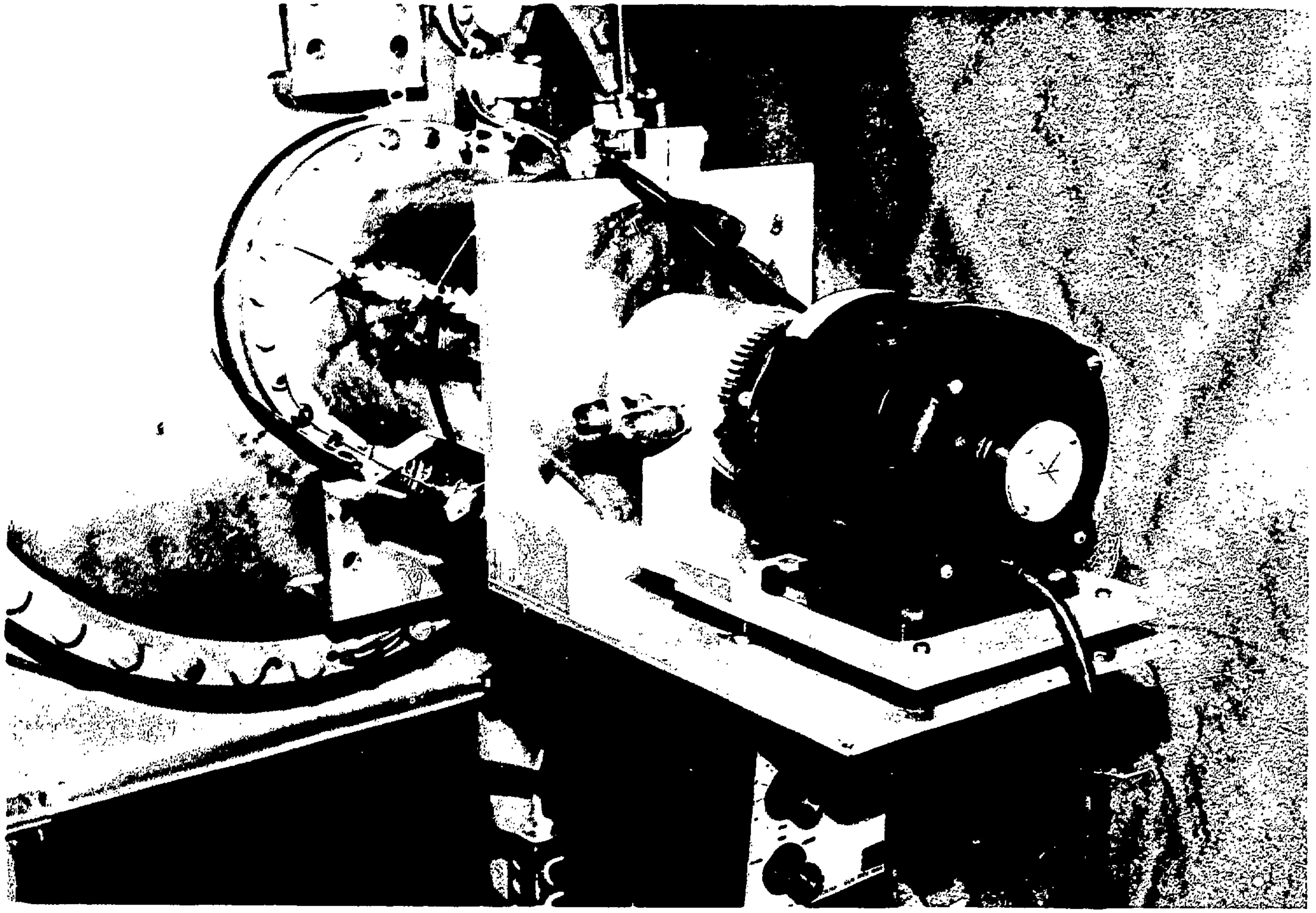


Figure 3. Closeup of Test Rig Attached to Vacuum Chamber

SECTION III

TASK I — DEVELOPMENT OF AN EXPERIMENTAL TECHNIQUE FOR FILM THICKNESS MEASUREMENT IN SLOW-SPEED LIGHTLY-LOADED ELASTOHYDRODYNAMIC CONTACTS

1. General

Section IV, Part I of this report discussed briefly the various techniques available to measure the oil film thickness in an EHD conjunction. The bearing race displacement technique, which was the one chosen to be developed in this program, was considered in detail, showing the derivation of an equation relating the total axial displacement of a dual bearing arrangement to the EHD film thicknesses at the ball-race conjunctions. Because of several assumptions that were made in the derivation of this equation, it was deemed necessary to conduct certain experiments in Task I, in order to ascertain the validity of determining the oil film thicknesses by the displacement measurement. Some of these experiments were conducted with the SwRI optical EHD tester, which was also described in Section IV, Part I of this report.

As noted in Part I of this report, the optical measurements showed that the central-region film thickness of SwRI Oil B in pure rolling was, under comparable operating conditions, considerably greater than the central-region film thicknesses of the other six oils in pure sliding. In all seven instances, the oil was supplied to the ball-disk conjunctions by means of jets in a "flooded" fashion. It was thought that this difference in central-region film thickness behavior might be due to the difference in thermal effects occurring in the conjunction inlet caused by pure sliding as against pure rolling. Accordingly, it was decided during this reporting period to obtain additional film thickness measurements for the oils in question under pure rolling conditions, and to compare these results with the previous results obtained in pure sliding. Moreover, it was reasoned that if a thermal effect should be observed in the central-region film thickness behavior, then a similar effect would likewise be found in the behavior of the minimum film thickness at the side lobes in the conjunction. Therefore, the analysis was also extended to the minimum film thickness behavior.

In the prior work performed at SwRI,(2) a straight mineral oil, designated as SwRI Oil B, was employed in EHD film thickness and friction measurements in pure rolling. The film thickness was determined by the optical interference technique, with a steel ball placed between two contrarotating glass disks. The ball diameter was varied three times: 1.91 cm (0.75 in.), 2.54 cm (1.00 in.), and 3.81 cm (1.50 in.). The load was also varied three times: 13.3 N (3.0 lb), 22.2 N (5.0 lb), and 33.4 N (7.5 lb). The sum velocity was varied five times, from 25.4 to 127 cm/sec (10 to 50 ips). The oil temperature at the conjunction inlet was approximately 27 C (80 F), and was measured and accounted for in the EHD calculations.

It was found in this work that the central-region and minimum film thicknesses obtained for the three ball sizes, three loads, and five sum velocities could be linearly correlated by appropriate dimensionless parameters. These correlations are presented in Figures 4 and 5, and the appropriate dimensionless equations are given below.

For the central-region film thickness:

$$H_c = 1.05\,\Sigma_c \tag{1}$$

where

$$H_c = \frac{h_c}{R} \tag{2}$$

$$\Sigma_c = \frac{(G\,U_t)^{0.74}}{(W')^{0.074}} \tag{3}$$

For the minimum film thickness:

$$H_m = 0.75\,\Sigma_m \tag{4}$$

where

$$H_m = \frac{h_m}{R} \tag{5}$$

$$\Sigma_m = \frac{G^{0.70}\,U_t^{0.77}}{(W')^{0.14}} \tag{6}$$

The various symbols employed in the above equations, and throughout this report, are

H_c = dimensionless central-region film thickness, defined by Eq. (2)

H_m = dimensionless minimum film thickness, defined by Eq. (5)

Σ_c = dimensionless material-velocity-load parameter for central-region film thickness correlation for circular conjunctions, defined by Eq. (3).

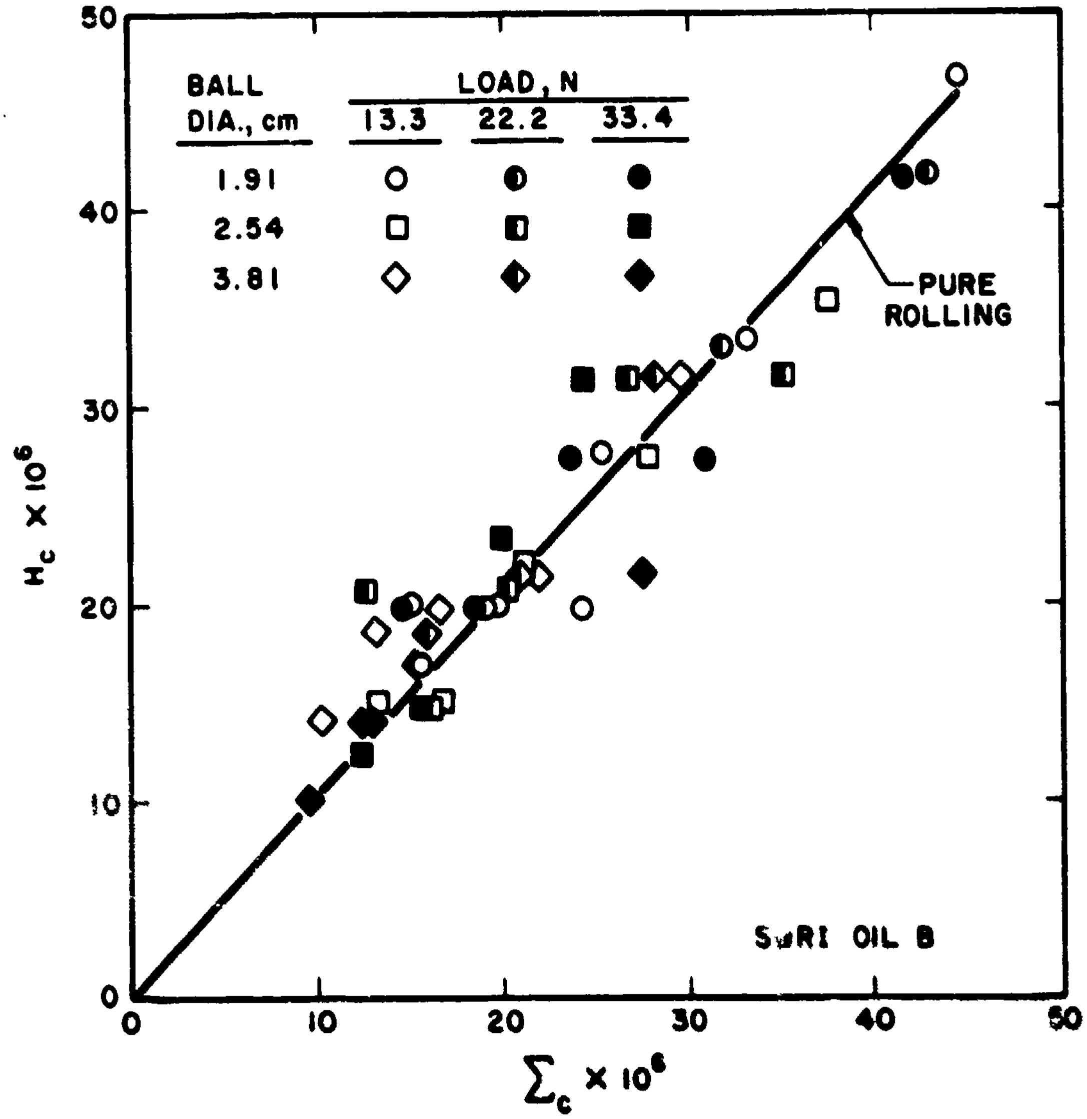


Figure 4. Dimensionless Central-Region Oil Film Thickness for SwRI Oil B in Pure Rolling

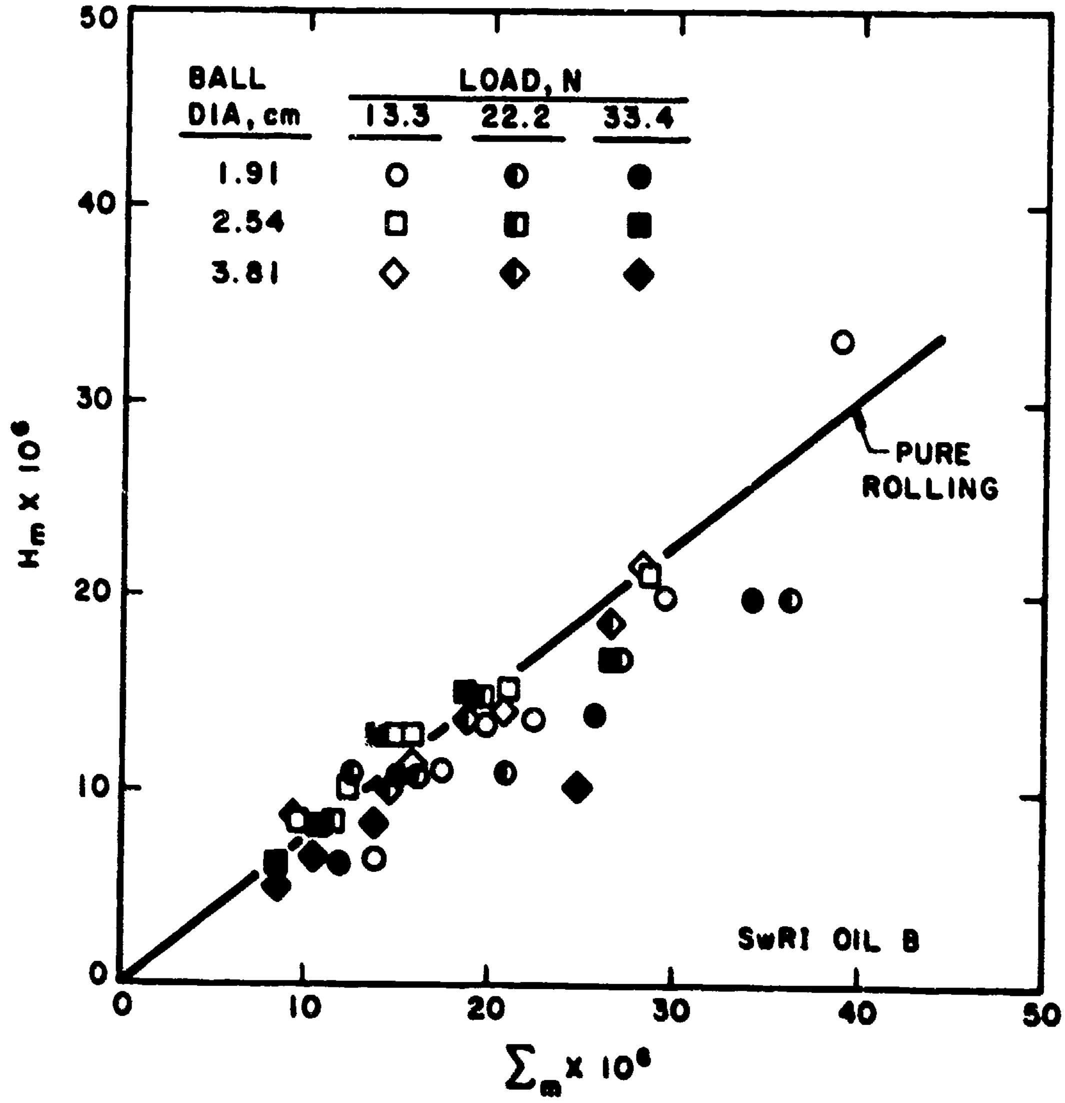


Figure 5. Dimensionless Minimum Oil Film Thickness for SwRI Oil B in Pure Rolling

Σ_m = dimensionless material-velocity-load parameter for minimum film thickness correlation for circular conjunctions, defined by Eq. (6)

h_c = central-region lubricant film thickness

h_m = minimum lubricant film thickness

R = equivalent radius of curvature = $(1/R_1 + 1/R_2)^{-1}$

R_1 = radius of curvature of body 1

R_2 = radius of curvature of body 2

G = dimensionless materials parameter = $\alpha_o \overset{*}{E}$

α_o = pressure-viscosity coefficient of lubricant at conjunction inlet temperature and near-atmospheric pressure

$\overset{*}{E}$ = equivalent elastic modulus

$$= 2\left[\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right]^{-1}$$

ν_1 = Poisson's ratio of body 1

ν_2 = Poisson's ratio of body 2

E_1 = elastic modulus of body 1

E_2 = elastic modulus of body 2

U_t = dimensionless sum velocity = $\dfrac{\mu_o V_t}{\overset{*}{E} R}$

μ_o = absolute viscosity of lubricant at conjunction inlet temperature and near-atmospheric pressure

V_t = sum velocity = $V_1 + V_2$

V_1 = surface velocity of body 1

V_2 = surface velocity of body 2

W' = dimensionless load = $\dfrac{P}{\overset{*}{E} R^2}$

P = load

It is interesting to note that Eq. (1) is the same in form as a correlating equation obtained by Archard and Cowking,(3) whose numerical constant in the equation was 0.84 instead of 1.05 as determined here. Moreover, Eq. (4) is identical in every respect to a correlating equation obtained by Westlake and Cameron.(4)

Figures 4 and 5 for SwRI Oil B and the two cited references employing other oils show that the relationships between H_c and Σ_c and between H_m and Σ_m in pure rolling are essentially linear up to values of Σ_c and Σ_m of about 45×10^{-6}. The implication is that, with values of Σ_c or Σ_m up to about 45×10^{-6}, any viscous heating effect in the conjunction inlet region(5) was probably quite small if the motion is pure rolling. It was noted in Part I of this report that the dimensionless central-region film thicknesses, H_c, of the six different test oils in pure sliding, when plotted against the dimensionless material-velocity-load parameter, Σ_c, were less than the H_c of SwRI Oil B in pure rolling. Accordingly, it appeared that the difference noted might have been due to some unusual thermal effect associated with the sliding motion. In an effort to resolve this question, additional tests in pure rolling were conducted on some of the test oils during the current reporting period. A discussion of these results, together with the previous results, will now be presented.

2. Optical EHD Film Thickness Results

The central-region film thickness results, obtained in both pure rolling and pure sliding, are summarized for four different formulations of Apiezon C oil in Figure 6, for Apiezon A (+ antioxidant + lead naphthenate) oil in Figure 7, and for Nye 860-2 (+ antioxidant + lead naphthenate) oil in Figure 8. For purposes of comparison, the pure rolling data for SwRI Oil B are shown in these figures as dash lines up to a Σ_c value of 45×10^{-6}, but with the data points omitted for the sake of clarity.

The data in each figure are for two loads of 17.70 N (3.98 lb) and 59.78 N (13.44 lb) and one ball size of 2.54 cm (1 in.). The conjunction inlet temperature for the pure sliding tests ranged between 26.7 and 37.8 C (80 and 100 F), whereas for the pure rolling tests it ranged between 26.7 and 28.9 C (80 and 84 F). The pure sliding data are taken from Part I of this report. The pure rolling data were obtained during this reporting period.

Referring to Figure 6, the pure sliding data were obtained for four different formulations of Apiezon C of very similar viscosity characteristics, and their central-region film thickness behaviors were also similar. Therefore, pure rolling tests were made on only one of these formulations, BBRC 36233, assuming that the other three formulations would behave similarly in pure rolling. It is seen that, considering the experimental scatter, the pure rolling data for BBRC 36233 appear to lie somewhere between the pure rolling data for SwRI Oil B and the pure sliding data for the

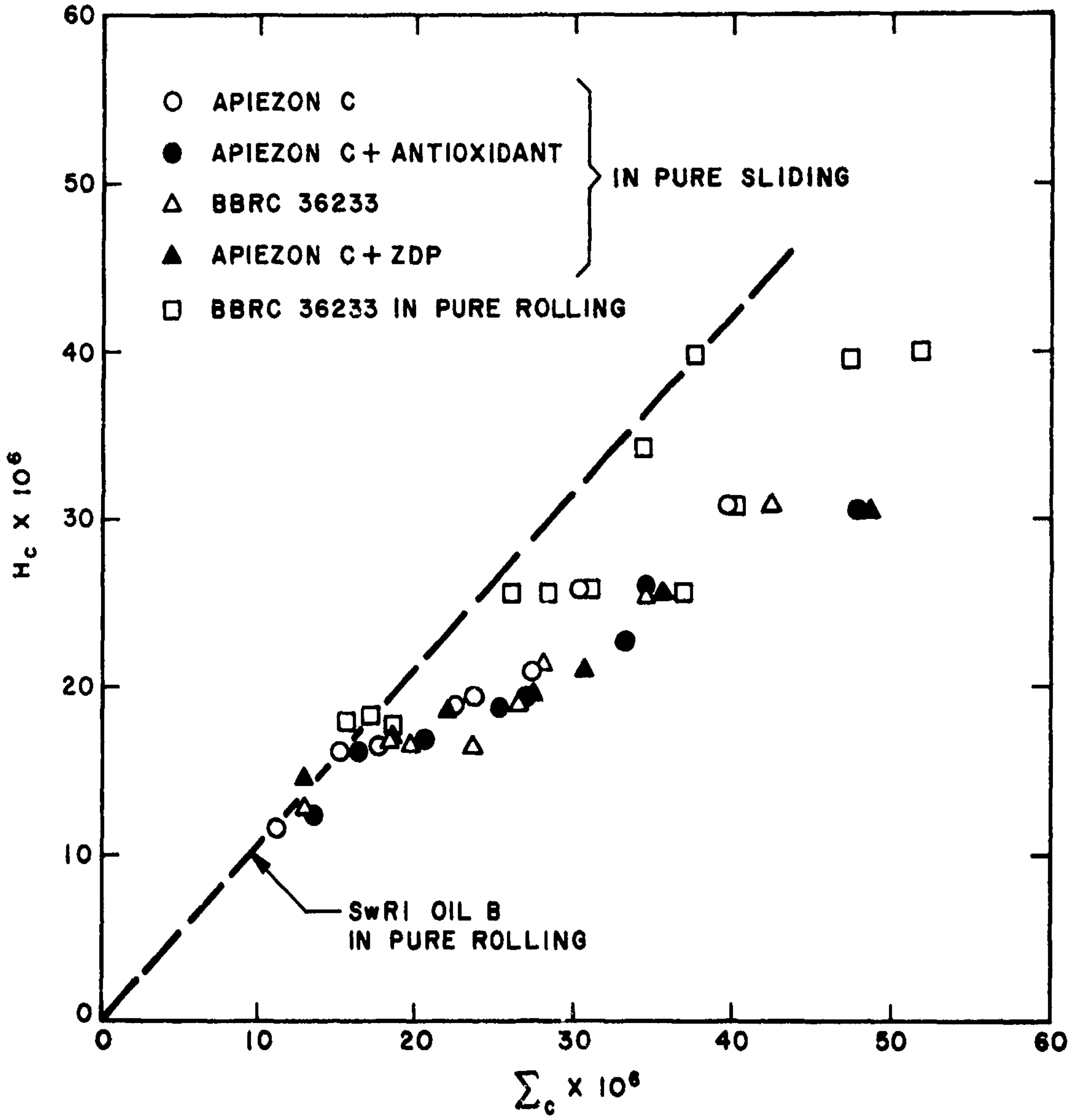


Figure 6. Dimensionless Central-Region Oil Film Thickness for Four Formulations of Apiezon C

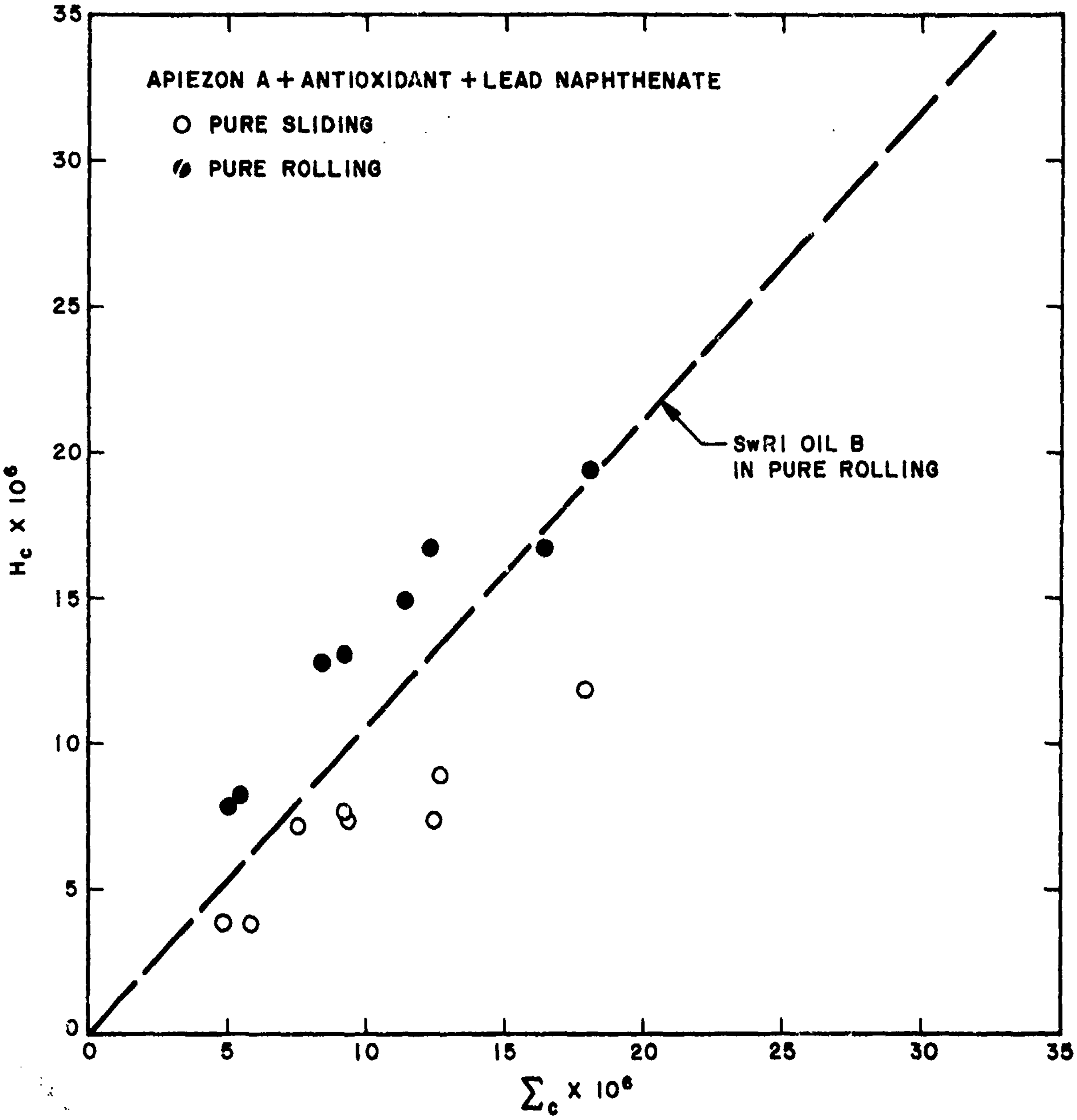


Figure 7. Dimensionless Central-Region Oil Film Thickness for Apiezon A

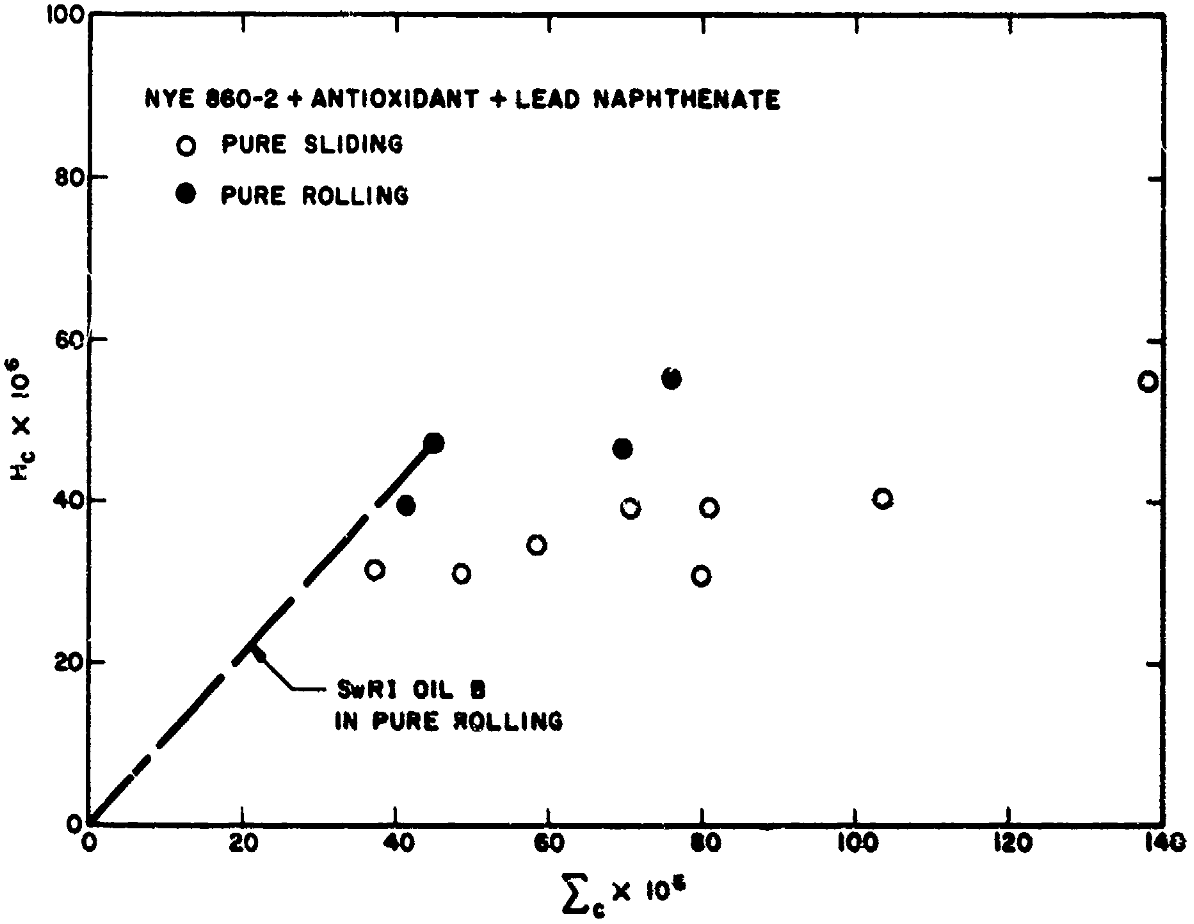


Figure 8. Dimensionless Central-Region Oil Film Thickness for NYE 860-2

Apiezon C formulations.

Figure 7 presents the pure rolling and pure sliding data for Apiezon A, which oil is less viscous than Apiezon C. Note that the pure rolling data for this oil appear to lie somewhat higher than the pure rolling data for SwRI Oil B.

Figure 8 shows the results for Nye 860-2, an oil more viscous than Apiezon C. It is seen that at values of Σ_c less than 45×10^{-6}, the pure rolling data for Nye 860-2 agree quite well with the pure rolling data for SwRI Oil B. However, at higher values of Σ_c, the linear H_c vs. Σ_c relationship begins to break down, due possibly to the increased viscous heating effect in the inlet region.

It must be recognized that experimental errors are inevitable in this type of measurement. Therefore, it is useful to compare all of the results together, in an effort to see how the data behave as a whole. This is done in Figure 9, which combines the data presented in the preceding figures by omitting the data points for the sake of clarity. In this figure, the long dashed line is the best-fit line for SwRI Oil B taken from Figure 4. The irregularly shaped boxes show the scatter range of data for the six test oils presented in Figures 6 through 8, with the solid boxes denoting the pure rolling data and the dashed boxes denoting the pure sliding data. Figure 9 suggests that the H_c versus Σ_c relationship is, in general, not linear in either the pure rolling or the pure sliding case, but can best be approximated by curves with progressively decreasing slopes as Σ_c is increased. This general trend is entirely reasonable, because the viscous shear and thus heating effect in the inlet region is expected to become progressively more severe with increasing Σ_c. As to the difference in the magnitudes of H_c between pure rolling and pure sliding, it is apparent that the velocity profile across the inlet film is skewed in the sliding case but symmetrical in the rolling case, so that the viscous shear effect is more pronounced in sliding and the friction coefficient is higher in sliding than in rolling. In other words, the character and thus magnitude of the viscous heating processes are different.

The general levelling trend of H_c at very high values of Σ_c, in both pure rolling and pure sliding, is not believed to be the result of inlet "starvation" in these tests. All these tests were performed with the oil supplied by jets to the conjunction inlet in a flooded fashion, and thus starvation was not likely. However, inlet starvation could be important in actual bearings. With the DMA bearings in which the oil is applied to the balls and races as relatively thin films, rather than by copious jets, starvation is far more likely.

During the current reporting period, all previously obtained and recently obtained results were analyzed to yield the minimum oil film thickness occurring at the side lobes in the conjunction. The corresponding H_m versus Σ_m data for pure rolling and pure sliding are presented in Figure 10 for four different formulations of Apiezon C, in Figure 11 for Apiezon A, and in

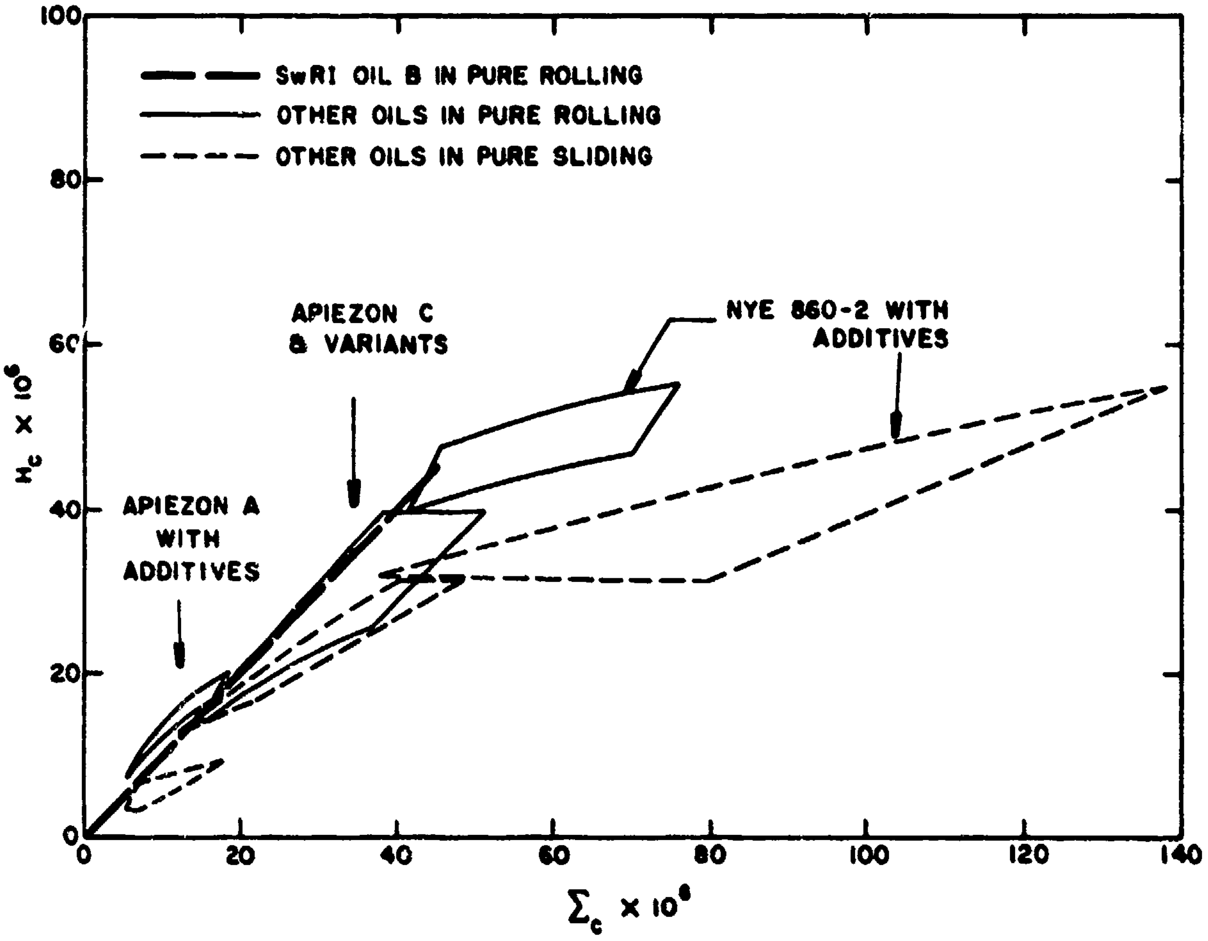


Figure 9. Dimensionless Central-Region Oil Film Thickness for Seven Oils

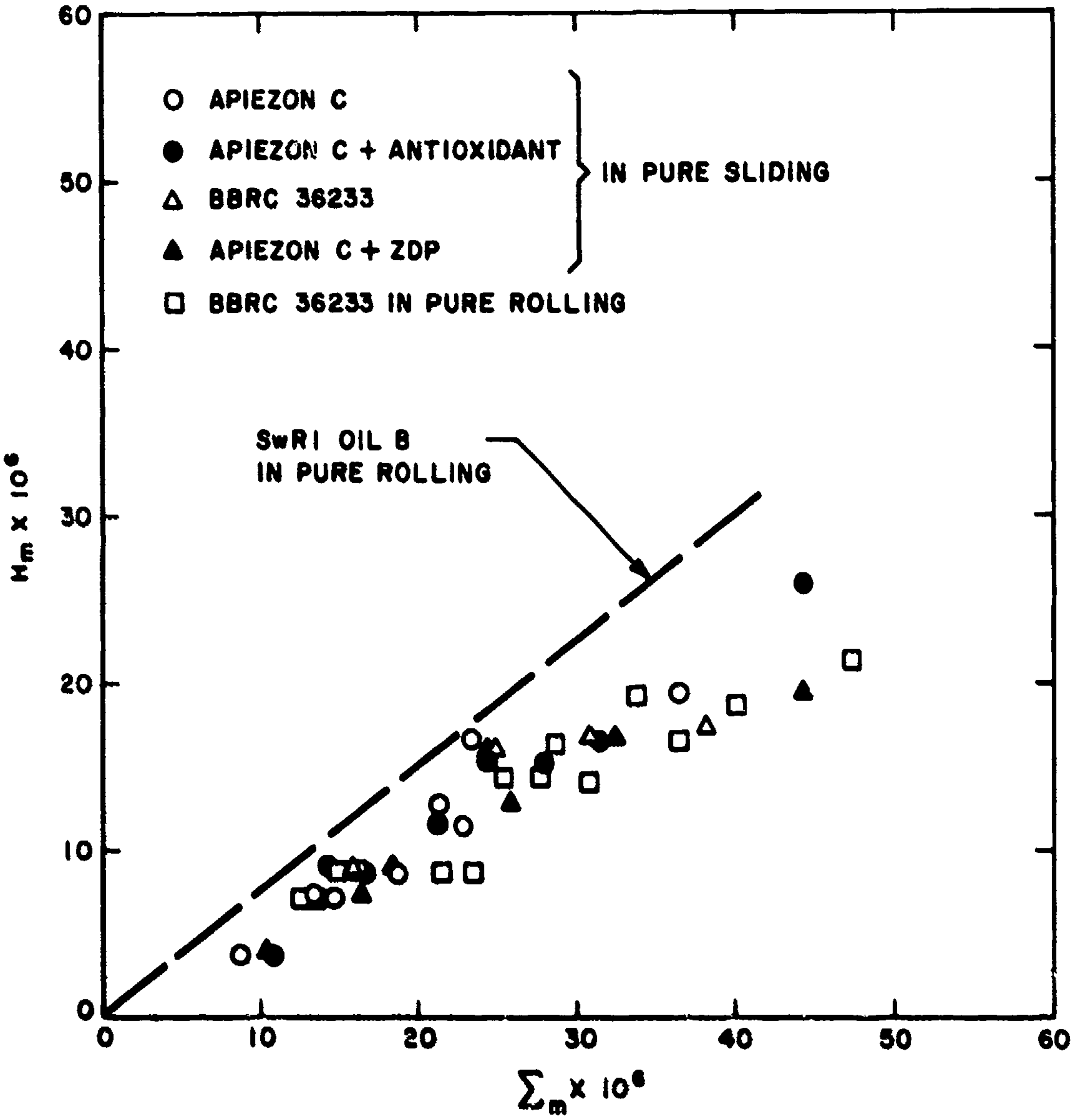


Figure 10. Dimensionless Minimum Oil Film Thickness for Four Formulations of Apiezon C

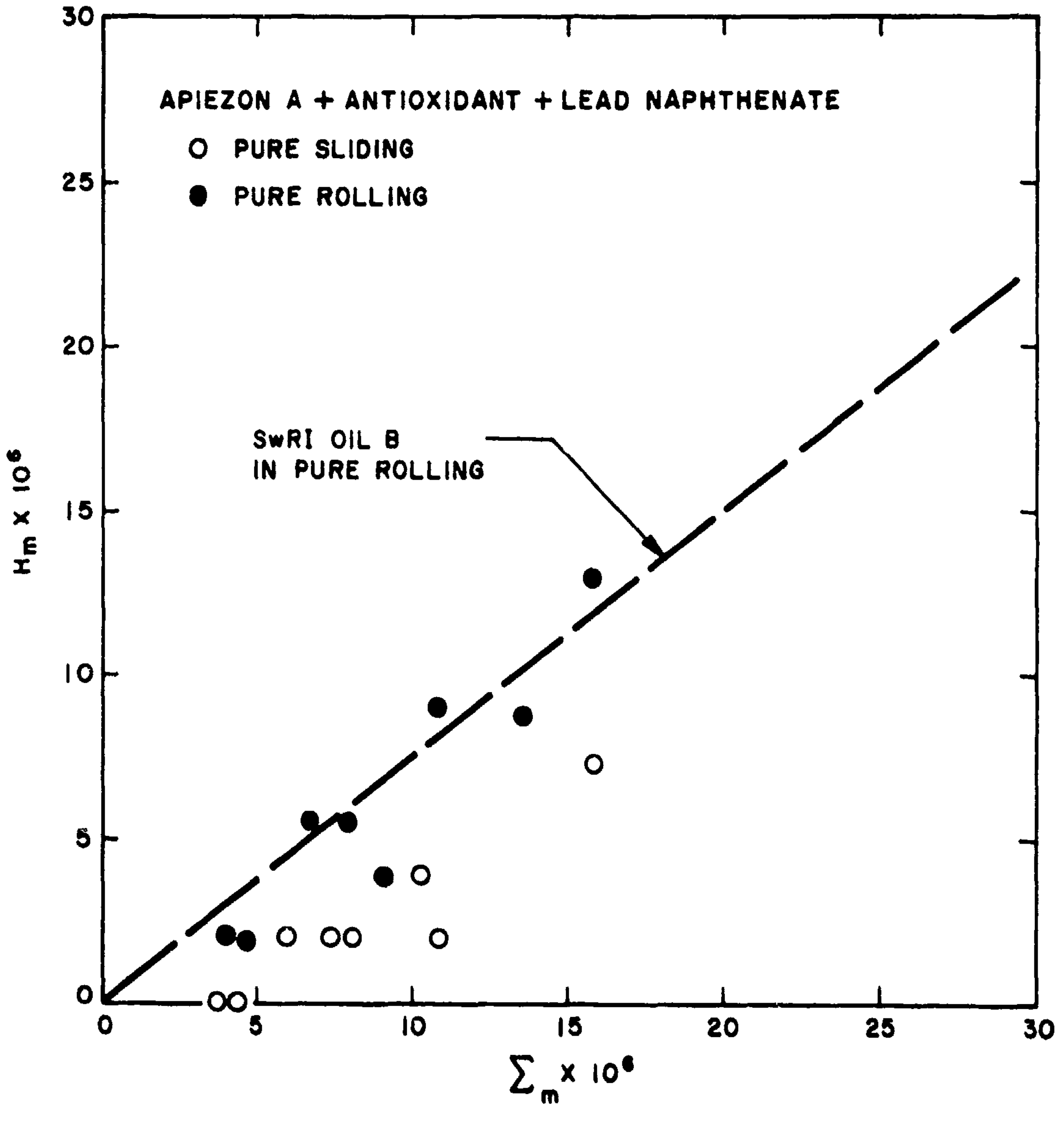


Figure 11. Dimensionless Minimum Oil Film Thickness for Apiezon A

Figure 12 for Nye 860-2, along with the pure rolling data for SwRI Oil B. The combined results for the seven oils are given in Figure 13. It is seen that these results are very similar in trends to the H_c versus Σ_c results presented in Figures 6 through 9, and the trends can basically be explained in a similar manner.

In conclusion, the linear H_c versus Σ_c and linear H_m versus Σ_m relationships, as represented by Eq. (1) and Eq. (4), respectively, incorporating the numerical correlating constants as given previously or as recommended by other investigators, appear to be approximations depending upon the range of the dimensionless material-velocity-load parameters, Σ_c and Σ_m, covered and also other details of the experiments (such as the possibility of inlet starvation, etc.). Where a flooded inlet can be assured, as in the case of these experiments, the H_c versus Σ_c and H_m versus Σ_m relationships appear to be nonlinear with progressively decreasing slopes as Σ_c or Σ_m is increased. The nonlinear trend appears to be largely dictated by thermal effects, and apparently little influenced by the oil composition as long as the operation is in the full elastohydrodynamic regime.

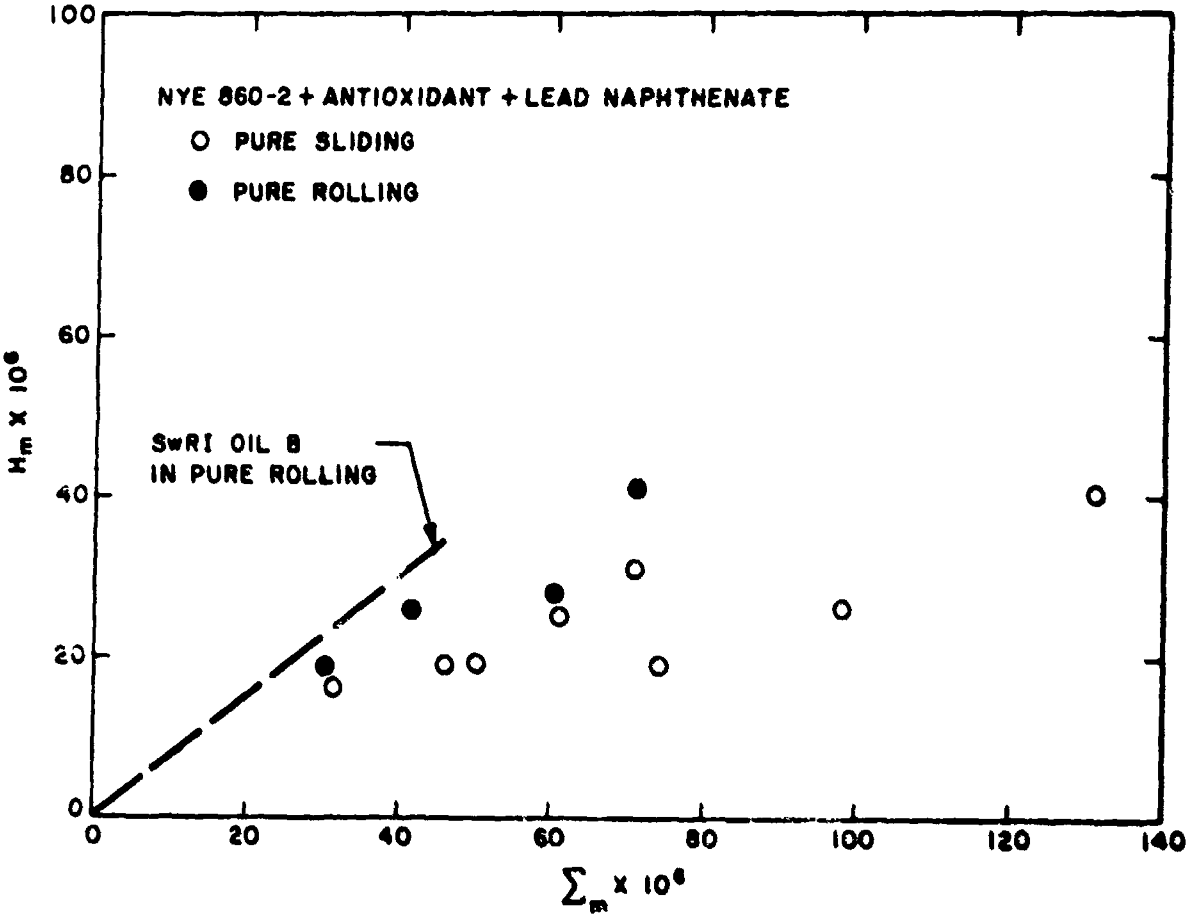


Figure 12. Dimensionless Minimum Oil Film Thickness for NYE 860-2

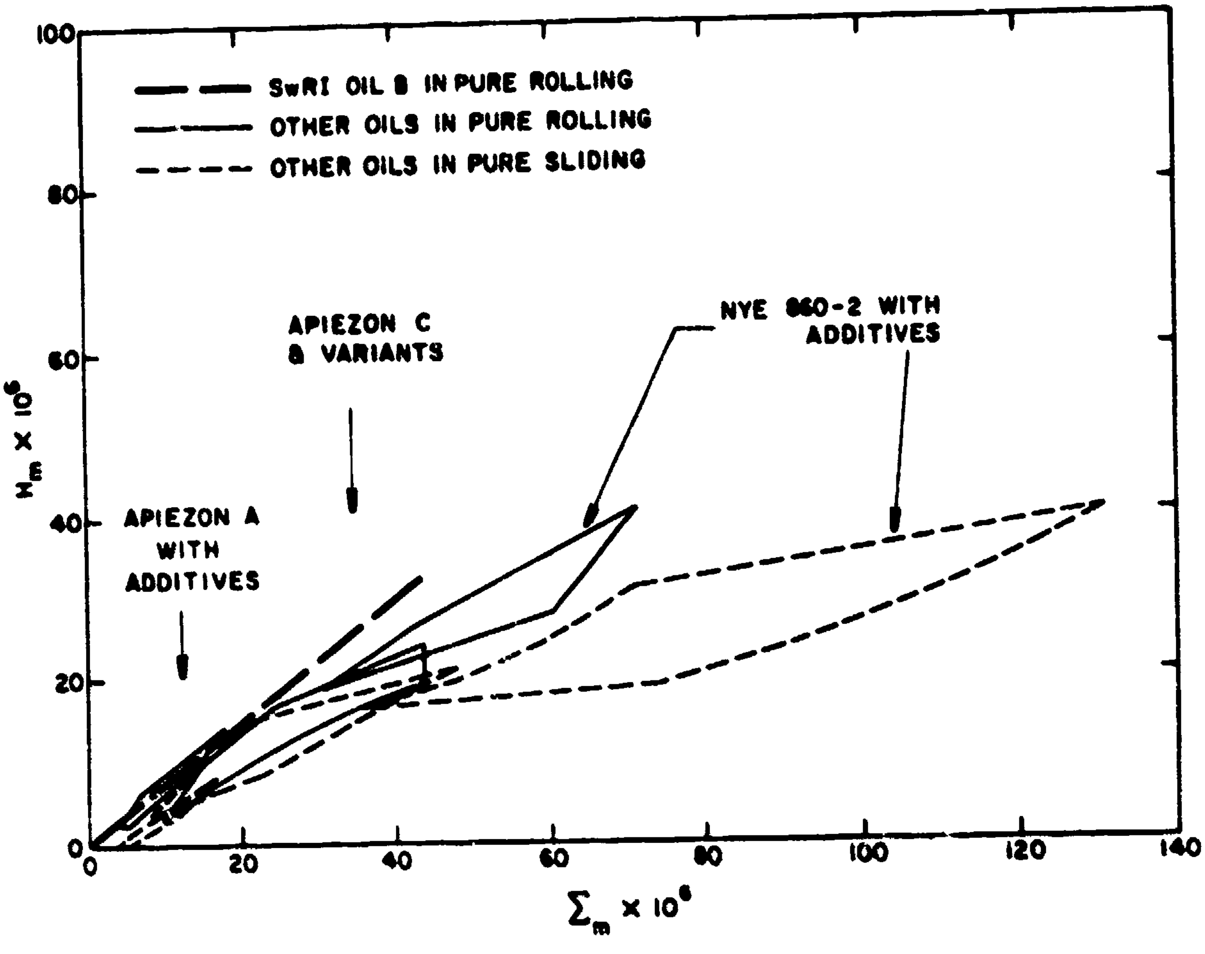


Figure 13. Dimensionless Minimum Oil Film Thickness for Seven Oils

SECTION IV

TASK II — EXPERIMENTAL MEASUREMENTS OF FILM THICKNESS IN TYPICAL DESPIN MECHANICAL ASSEMBLY BEARINGS OPERATING IN A SIMULATED SPACE ENVIRONMENT

1. General

The purpose of this task, as stated in Section V, Part I of this report, is to make quantitative measurements of oil film thicknesses in the EHD conjunctions of typical DMA bearings operating in a simulated space (vacuum) environment. As previously outlined, the measurements consider the following properties and operational variables, and their influence on the formation of an EHD oil film:

a. oil viscosity

b. additive effects

c. degree of oil supply to the inlet region

d. ball-race surface roughness

e. temperature

f. load

g. speed

It was stated in Part I of this report that there would be no major variations in temperature for these Task II tests, with the room temperature being controlled at normal room conditions which would be approximately 25 C (77 F). For the purpose of obtaining additional information from the Task II experiments, the test procedure was modified to include axial displacement measurements of the bearing outer race at three different conditions (prepumpdown, initial after pumpdown, and 24 hours after pumpdown), instead of the original initial after pumpdown condition only. For the prepumpdown and initial after pumpdown results, measurements were made immediately after putting the test bearings into motion. Therefore, the bearings and oils were at the controlled room temperature. For the 24 hour after pumpdown results, the test bearings were allowed to seek an equilibrium temperature for normal operation of the bearings running at 100 rpm. Thus, it was possible to observe the effect of temperature, over a moderate range, on the formation of an EHD film. In other words, the bearings ran continuously at 100 rpm between the initial after pumpdown and the 24-hour after pumpdown measurements, reaching equilibrium temperatures for the appropriate test conditions.

The bearing test chamber, vacuum chamber, and associated instrumentation that were employed in this task have been described in detail in Section II, Part I, and Section II, Part II of this report and will not be repeated here.

The modified test procedure for each test in Task II was as follows: The bearings were installed in the test chamber with the proper axial preload applied to the bearings. For tests where lubricant reservoirs were employed, the reservoirs were also installed in the test chamber at this time. After the test chamber was attached to the vacuum system, but prior to pumpdown, the LVDT system was zeroed with the drive shaft not rotating. Then measurements of race displacement of the outer race of the floating bearing (forward) were rapidly made under steady operating conditions at a base speed and four speed levels of 50, 100, 150, and 200 rpm. The base speed selected was the slowest that could be attained that would maintain a steady bearing speed. This base speed created a baseline race displacement trace from which the displacements at the four other speed levels could be measured; this was necessary because of runouts in the bearings. All bearings, regardless of the precision incorporated in fabrication, will exhibit some wobble or axial runout. Typical of the axial runout measurements that have been determined in this experimental program are 50×10^{-4} to 125×10^{-4} mm (200 to 500 μin.) for two bearings axially preloaded against each other and running at speeds up to 200 rpm. These runouts are easily detected and measured with the LVDT system and are normally displayed graphically as a sine wave or some variation thereof. When the pair of bearings, installed in the test rig and properly instrumented, are rotated very slowly, this sine wave will be generated and recorded using the LVDT and associated instrumentation. Then if the driving speed of the bearings is increased, the runout wave will be displaced from its initial position by an amount depending upon the oil film thicknesses generated in the two bearings. The base speeds for Task II tests performed varied over a range of 7 to 37 rpm. Bearing torque and temperatures were also measured at the four speed levels. It was found that the bearing temperatures did not change measurably when obtaining data if they were collected rapidly, starting with the base speed and proceeding through the four speed levels in the order of increasing speed. Also, it was found that more meaningful EHD film thickness measurements were obtained by following this increasing-speed procedure. Duplicate measurements were made for each of the four speed levels relative to a new base speed measurement. After the prepumpdown results were obtained, the bearing test rig was stopped and the test chamber was pumped down until a stable pressure was achieved. Then repeat measurements of race displacement under vacuum conditions were performed according to the same procedure as outlined above for the prepumpdown measurements. At the conclusion of these initial after pumpdown measurements, the bearing test rig was left running at a constant speed of 100 rpm for 24 hours. At the end of the 24-hour period, repeat measurements of race displacement, bearing torque, and bearing temperatures were made exactly according to the procedure employed for obtaining the prepumpdown and initial after pumpdown results. Again, duplicate measurements were obtained. This procedure was repeated for the two axial load levels. From these measurements, the film thicknesses were determined using a computer program which solves the race displacement versus oil film thickness relationship. Development of this computer program and presentation of the computed results will be presented later.

Based on experiments discussed in Section IV, Part I of this report, it is concluded that the effects of thermal expansion are probably negligible for the speed range examined in the present program. Precautions were taken, however, when the film thickness measurements were made in Task II, to minimize any error that could be caused by thermal expansion effects. This was done by obtaining the displacement measurements as rapidly as possible following a speed change thus allowing a minimum amount of time for any thermal expansion to occur. In addition, a new zero reading to account for any instrument drift was determined immediately prior to making displacement measurements.

2. Development of Computer Program to Analyze Test Results

In Part I of this report, an equation was developed to relate the measured axial displacement of the outer race of the bearing located in the diaphragm mounting ring to the EHD film thicknesseses between the balls and races in the bearings. The equation as developed in Part I is

$$\Delta L_y = 2 \left\{ 0.025 \left[0.43837 - \sin \left[\arc \cos \left(\frac{0.02247}{0.025 - 2\, h_c} \right) \right] \right] + 2\, h_c \sin \left[\arc \cos \left(\frac{0.02247}{0.025 - 2\, h_c} \right) \right] \right\} \quad . \qquad (7)$$

where ΔL_y is the total axial displacement of the outer race of the bearing in the diaphragm mount as measured by the LVDT shown in Figure 1. This total displacement is the result of the development of EHD films at the inner and outer ball-race conjunctions in two bearings.

It was assumed in the derivation of Eq. (7) that the same film thickness existed at both the inner and outer ball-race contacts in both bearings. Two oversimplifications are involved in that assumption. First, in either bearing, the EHD film thickness at a ball-outer race contact will differ from that at a ball-inner race contact because of geometry effects. From theory and experiment, it is well known that due to better conformity of the ball and outer race, the film thickness will be thicker there than at the ball-inner race contact. For the bearings employed in the present work this difference amounts to about 10 percent. Second, due to different heat transfer paths, the operating temperatures of the two bearings in the test rig can be different, and this affects the viscosity of the oil and consequently the EHD film thickness. Depending upon the magnitude of this temperature difference, the EHD film thickness in one bearing can differ from the EHD film thickness at the corresponding location in the other bearing by as much as 20 percent. When the combined effects of geometry and temperature difference are considered, it is felt desirable to account for them when calculating the EHD film thicknesses in the two bearings from the displacement measurements. To do this requires a system of equations rather than the simple Eq. (7). Briefly, the procedure involves first solving an equation similar to Eq. (7) for the EHD film thickness at the ball-inner race contacts of the aft bearing. Then, using the known empirical relationships for the effects of geometry and viscosity on the EHD film thickness, the film thickness at the ball-outer race contacts of the aft bearing and the film thickness at the ball-inner race and ball-outer race contacts of the forward bearing can be calculated.

Further complicating the task of accounting for the effects of contact geometry within a bearing, and temperature difference between bearings, is the fact that, according to theory, a difference in contact geometry will have different effects on the minimum EHD film thickness and the central-region EHD film thickness. The same is true of the effect of viscosity. Consequently, in order to account for the geometry and viscosity effects on the EHD film thicknesses in the bearings, one must assume that it is either the minimum or the central-region EHD film thickness that is responsible for the displacement ΔL_y, being measured. Unfortunately, as was discussed in Part I of this report, it is not possible to determine from the results of Task I whether it is the minimum or central-region EHD film thickness that is responsible for the displacement. Therefore, in the reduction of the displacement data from Tasks II and III, the film thicknesses in the bearings were calculated in two ways, first by using a system of equations developed by assuming that ΔL_y is due to the central-region EHD film thickness, and next by using a system of equations developed by assuming that ΔL_y is due to the minimum EHD film thickness.

Since the development of the two systems of equations for calculating the EHD film thicknesses from the bearing displacement data is rather detailed and lengthy, this is included in Appendix I. As shown in Appendix I, in order to avoid confusing the theoretical values of EHD film thicknesses, calculated using the theoretical equations of Grubin (6) and Dowson (7), with the experimentally-determined values of the EHD film thicknesses obtained from the race displacement measurements, different symbols are used. In accordance with the standard symbols used earlier, h_c, h_m, H_c, and H_m are the symbols reserved for the theoretical central-region, minimum, dimensionless central-region, and dimensionless minimum EHD film thicknesses respectively. For the film thicknesses determined from the race displacement measurement, the symbols h, h', H, and H' are used to denote the minimum, central-region, dimensionless minimum and dimensionless central-region EHD film thicknesses respectively. Throughout the report, comparisons of the EHD film thicknesses calculated from the measured bearing displacement data in these two ways are compared with the theoretical equations of Grubin for H_c and Dowson for H_m.

3. Experimental Test Results

As discussed above, a computer program was developed to compute the four different conjunction film thicknesses for the DMA bearings tested in Task II. A listing for the Task II data reduction program is given in Appendix II, while a sample printout of the Task II data is shown in Appendix III.

The best available expression for the central-region EHD film thickness in a flooded isothermal rectangular conjunction is due to Grubin$^{(6)}$ and is given by

$$H_c = 1.18\, \Sigma_G \qquad (8)$$

where Σ_G = Grubin's dimensionless material-velocity-load parameter for rectangular conjunctions

$$= \frac{G^{0.73} U_t^{0.73}}{W^{0.09}}$$

W = dimensionless load = $\dfrac{w}{\overset{*}{E}R}$

w = load per unit width

and the other symbols are defined after Eq. (6).

While the central-region EHD film thickness is important to the present study, the minimum EHD film thickness is also extremely important. As is now well known, the oil film thickness profile in a rectangular conjunction is very nearly flat throughout, modified principally by a constriction in the exit region. This constriction, which is straight across the flow path for a rectangular conjunction, and almost straight for a high aspect ratio elliptic conjunction, results in a minimum oil film thickness within the conjunction, so that if surface-to-surface contact is to occur, it is apt to occur here first. Thus, the importance of predicting the minimum EHD film thickness in a bearing is evident.

Based upon theoretical analyses and considerable experimental data, Dowson $^{(7)}$ recently proposed the following equation for computing the minimum oil film thickness in a flooded isothermal rectangular conjunction:

$$H_m = 1.63\ \Sigma_D \tag{9}$$

where Σ_D = Dowson's dimensionless material-velocity-load parameter for rectangular conjunctions

$$= \frac{G^{0.54} U_t^{0.70}}{W^{0.13}}$$

and the other symbols are given after Eq. (6) and Eq. (8).

Equation (9) is believed to be the best expression available for calculating the minimum film thickness for the rectangular or high aspect ratio elliptic conjunction with flooded, isothermal flow.

When the film thickness equations for rectangular conjunctions are used to calculate the film thickness in elliptic conjunctions, an equivalent load per unit width $^{(8)}$ is used. For a bearing with elliptic conjunctions, as in this study, the dimensionless load per ball is given by

$$W_e = \frac{w_e}{\overset{*}{E}R} \tag{10}$$

where w_e = equivalent unit load per ball = $\frac{3P}{4a}$

P = normal load per ball

a = semiwidth of major axis of contact ellipse at ball-raceway contact

and $\overset{*}{E}$ and R are as previously defined. Therefore, the W_e in Eq. (10) replaces W in both Eqs. (8) and (9) for angular contact bearings.

The above equations were presented and discussed in detail in Section II, Part I of this report but were repeated here because they were used extensively in analyzing the Task II data. As noted, all of the plotted Task II experimental data that are presented in the following graphs are compared with these equations. Also, Eqs. (8) and (9) were used to calculate H_c and H_m at the base speed. These calculated values were then added to the film thicknesses determined from ΔL_y to obtain H and H' plotted in the following graphs.

Since the four different conjunction films for each test condition were calculated from a single displacement measurement, ΔL_y, they all followed similar patterns, although, the magnitudes of each would vary a few percent. The variance between inner and outer race film thickness are the result of a geometrical difference in the ball-race contacts, whereas the difference between aft- and forward-bearing contact film thickness values are a result of temperature differences between the two bearings.

Figure 14 shows typical film thickness values, calculated from the race displacement measurements, for the inner and outer contacts of the forward and aft bearings. The data were obtained prior to pumpdown for bearings treated with BBRC 36233. The dimensionless film thicknesses H and H′ are plotted against the dimensionless parameters Σ_D and Σ_G respectively, which were defined and discussed earlier in this section of the report. As can be seen in the figure, the film thicknesses at all four locations display the same trends. Although there are slight load effects shown by the data at the larger dimensionless parameter values, a single straight line drawn through the experimental data for either H or H′ would represent all the data very well. Of course, 24-hr after pumpdown results would display variance between the aft and forward bearings due to temperature differences, but as will be seen later these effects would be well correlated by the dimensionless parameters. Normally, the prepumpdown and initial after pumpdown results would not show an appreciable temperature difference between the aft and forward bearings, while the 24-hr after pumpdown results would exhibit a 1 to 4C (2 to 7F) temperature spread. This was not the case for tests using Nye 860-2 with antioxidant and lead naphthenate. Of all the oils tested, this one has the highest viscosity. The torque capability of the driving magnetic coupling was not great enough to turn the bearings lubricated with this oil at normal room temperature. Therefore, heat lamps directed at the bearing rig chamber were employed to raise the temperature enough to allow thinning of the lubricant until some test data could be obtained. Even then, it was not possible to turn the bearings at the higher speed levels.

Since as indicated in Figure 14 the experimental film thickness data for the four different conjunction locations behave similarly, the data for all will not be presented. The aft bearing outer race contact data were arbitrarily selected for further analysis and comparison, and all of the Task II plotted data shown in the following graphs will be values for those contacts. For purposes of generality, all of the film thickness data are presented in dimensionless form. However, the dimensional value of film thickness may be obtained by multiplying the dimensionless film thickness H or H′ by the equivalent radius at the ball-outer race contacts, R_o, which is 8.84352 mm (0.34817 in.).

A summary of all bearing tests for Task II is presented in Table II. As seen in the table, a total of four test series were run and each series was designed to isolate the effects of an oil property or design variable. For each test within a series, the operating variables were load and speed. Two load levels were used, the minimum of 222-N (50-lb) axial load, and the maximum of 890-N (200-lb) axial load as prescribed in the Statement of Work. Only two load levels were selected because of the extremely weak dependence of the oil film thickness on load, as was shown in the EHD film thickness equations. Because the oil film thickness is more sensitive to the conjunction sum velocity,

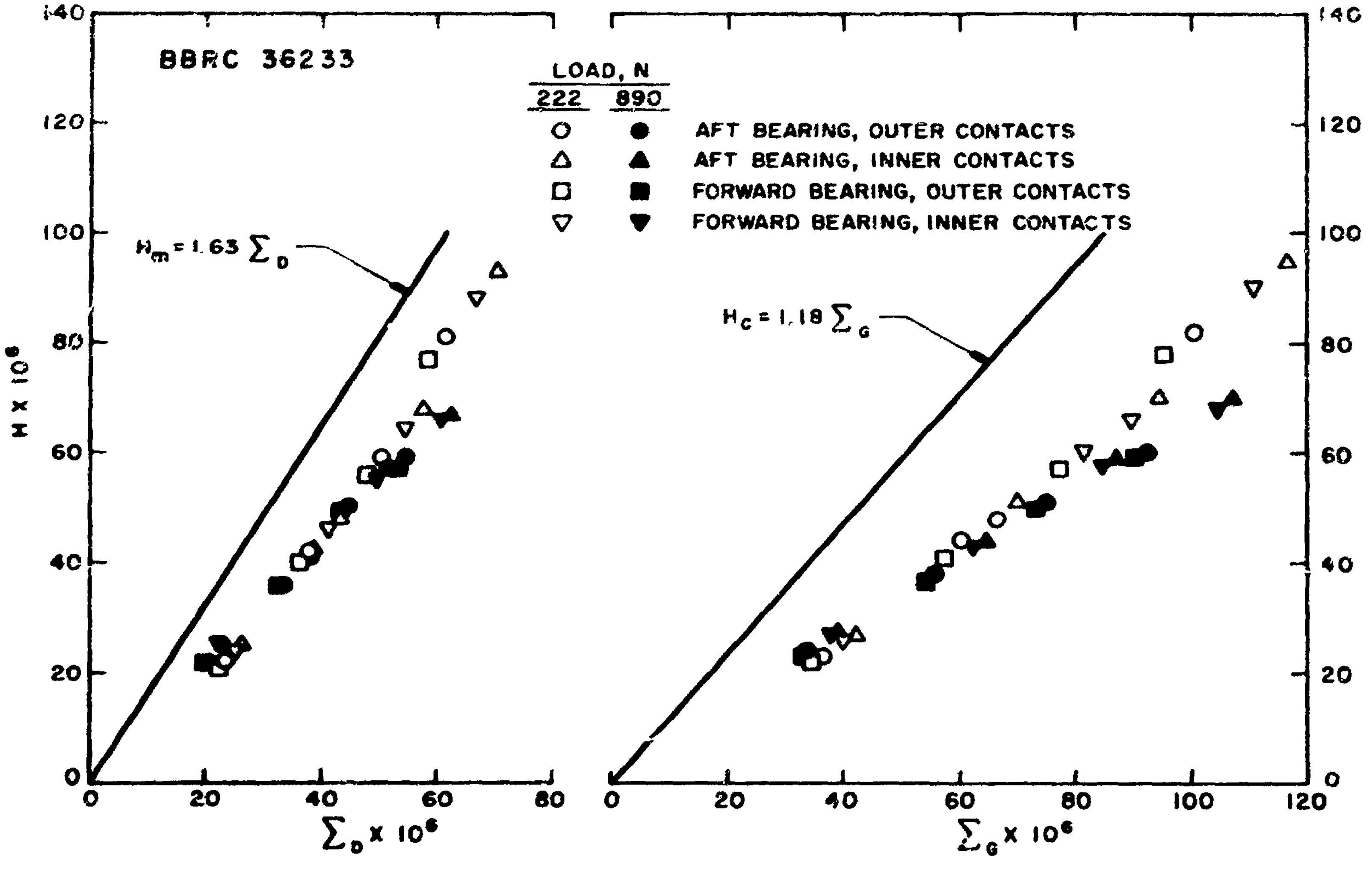


Figure 14. Dimensionless Prepumpdown Oil Film Thicknesses for Standard Bearings Having Thick Initial Film of BBRC 36233

TABLE 2. SUMMARY OF TASK II TESTS

Test Series	Variable Studied	Viscosity at 25 C (77 F), $m^2/s \times 10^6$	Additive Package	Initial Oil Film Thickness	Ball-Race Surface Roughness	Common Tests
I	Oil Viscosity	54	BBRC standard	Thick	MRC standard	
		225	BBRC standard	Thick	MRC standard	x
		1000	BBRC standard	Thick	MRC standard	
II	Additives	225	1.5% antioxidant	Thick	MRC standard	
		225	BBRC standard	Thick	MRC standard	x
		225	2.5% ZDP	Thick	MRC standard	
III	Initial Thickness of Applied Oil Film	225	BBRC standard	Thick	MRC standard	x
		225	BBRC standard	Thin	MRC standard	0
IV	Ball-Race Surface Roughness	225	BBRC standard	Thick	MRC standard	x
		225	BBRC standard	Thick	Roughness doubled	
		225	BBRC standard	Thin	MRC standard	0
		225	BBRC standard	Thin	Roughness doubled	

TEST CONDITIONS:

Pressure = equilibrium vapor pressure of test oil
Temperature ≈ 25 C (77 F)
Load = 222, 890 N (50, 200 lb) (2 load levels)
Speed = 50, 100, 150, 200 rpm (4 speed levels)

OIL BASE STOCK DESCRIPTION:

High viscosity oil = Nye 860-2
Intermediate-viscosity oil = Apiezon C
Low viscosity oil = Apiezon A

ADDITIVE PACKAGE:

BBRC standard = 1.5% antioxidant + 5% Lead naphthenate four levels of bearing speed above the base speed were used for each test within a series, 50, 100, 150, and 200 rpm, except for the high viscosity oil where the torque capability of the driving magnetic coupling was not sufficient to achieve the higher speeds.

As seen in the table, for all tests the environmental pressure in the bearing test chamber was to be the equilibrium vapor pressure of the test oil. It was found that the vapor pressure for formulations of Apiezon C, as calculated from the vapor pressure equation and constants given in Section II, Part I of this report, could not be achieved even with extended pumping time. On the other hand, it was not difficult to obtain the vapor pressure for Apiezon A as predicted by this same equation. This suggests that there might be an error in the constants in the equation for Apiezon C. As stated in Section II, Part I, the constants have not been determined for the Nye 860-2 oil, although limited weight-loss data obtained from evaporation cell measurements at BBRC indicate that its vapor pressure may not be greatly different from that of Apiezon C. Also, as seen in the table, for all tests the room temperature would be held approximately constant at about 25C (77F). Bearing temperatures that varied moderately from 25C (77F), especially in the 24-hr after pumpdown tests, were handled satisfactorily by the EHD film thickness equations showing no consistent disagreement with the other data.

Also as seen in Table II, two initial oil film thickness coatings on the bearings were investigated. These are designated in the table simply as "thick" and "thin". For the "thick" initial oil film tests, oil impregnated reservoirs were installed in the test chambers. For the "thin" initial oil film tests, no reservoirs were used.

Each test series shown in Table II along with plotted data representing that test series will be discussed separately in the following paragraphs. Highlights of these data will be pointed out and conclusions will be drawn later based on these test results.

Test Series I. In this test series the effect of oil viscosity on the oil film thicknesses formed in the EHD conjunctions of the bearings was studied. Three separate tests were conducted, one with each of three test oils of different viscosities, a low-, medium-, and a high-viscosity oil as shown in Table II. Each oil contained the same BBRC standard additive package, which is 1.5 percent antioxidant and 5 percent lead naphthenate. The initial oil film thickness was "thick film" which was about 30×10^{-4} to 40×10^{-4} mm. The bearings had the standard surface finish on the raceways, hereinafter referred to simply as "MRC standard." As discussed earlier in this section of the report, only part of the high-viscosity oil tests were achieved because of the excessive torque required to drive the bearings, especially at the higher speeds and at normal room temperatures.

Looking at Figures 15, 16, and 17, it is clear that the measured dimensionless film thicknesses increase with increasing viscosities when plotted against either Dowson's or Grubin's dimensionless parameters. Whereas Grubin's Eq. (8) predicts a slope of 1.18 as shown by the solid curve drawn on the righthand graphs in each figure, a best-fit line drawn through the low-viscosity oil, a formulation of Apiezon A, would exhibit a slope that would be considerably less, having a value of approximately 0.63. Likewise, as seen in Figure 16, the medium-viscosity oil, a formulation of Apiezon C (BBRC 36233), would exhibit a slope of approximately 0.73 and as seen in Figure 17, the high-viscosity oil, a formulation of Nye 860-2, would have a slope approximately the same as predicted by Grubin. Going to the lefthand graphs shown in Figures 15, 16, and 17, and comparing the measured dimensionless film thicknesses, H, to Dowson's Eq. (9), it is seen that the same trend is exhibited. These experimental results show that both the low-viscosity (Apiezon A) and medium-viscosity oil (BBRC 36233) have a slope less than predicted by Dowson. On the other hand, the data for these two oils agree better with Dowson's equation than Grubin's central-region film thickness equation. The experimental results for the high-viscosity oil (Nye 860-2) appear to have a slope slightly higher than predicted by Dowson, but agree very well with Grubin. Post-test examination of bearings show that these three oils, as employed in these tests, appear to provide film thicknesses adequate to place operation in the full EHD regime. But the plotted data indicate that only the high-viscosity oil, Nye 860-2 with antioxidant and lead naphthenate, is operating in the flooded conjunction regime, therefore agreeing with the theoretical equations. Although the low-viscosity and medium-viscosity oils seem to have adequate oil film thicknesses to prevent asperity contact, there does appear to be limited lubricant starvation causing films less than predicted by either Dowson or Grubin. Although the high-viscosity oil does agree very well with the theoretical flooded isothermal flow equations, large torques are required to drive bearings supplied with this oil making it undesirable as a DMA bearing lubricant.

In general the viscosity effects for these three oils do not appear to be completely correlated by Grubin's or Dowson's parameters. Using measured ΔL_y values for calculating film thicknesses H, and H′ which are then compared to both relationships appear to show better correlation between the minimum film thickness equation and the measured values, H. Of course these were short duration tests and do not predict what might happen under extended vacuum conditions.

Test Series II. This series was conducted to determine the effect of additives on the oil film thicknesses in the EHD conjunctions of the bearing. For these tests the intermediate-viscosity oil was used and the first test as shown in Table II was conducted using this oil without the antiwear additive, but the antioxidant additive was retained. Note that the second test in this series was common to Series I, where the same oil with the additive package was used, thus only two tests were required in Series II. The third test shown

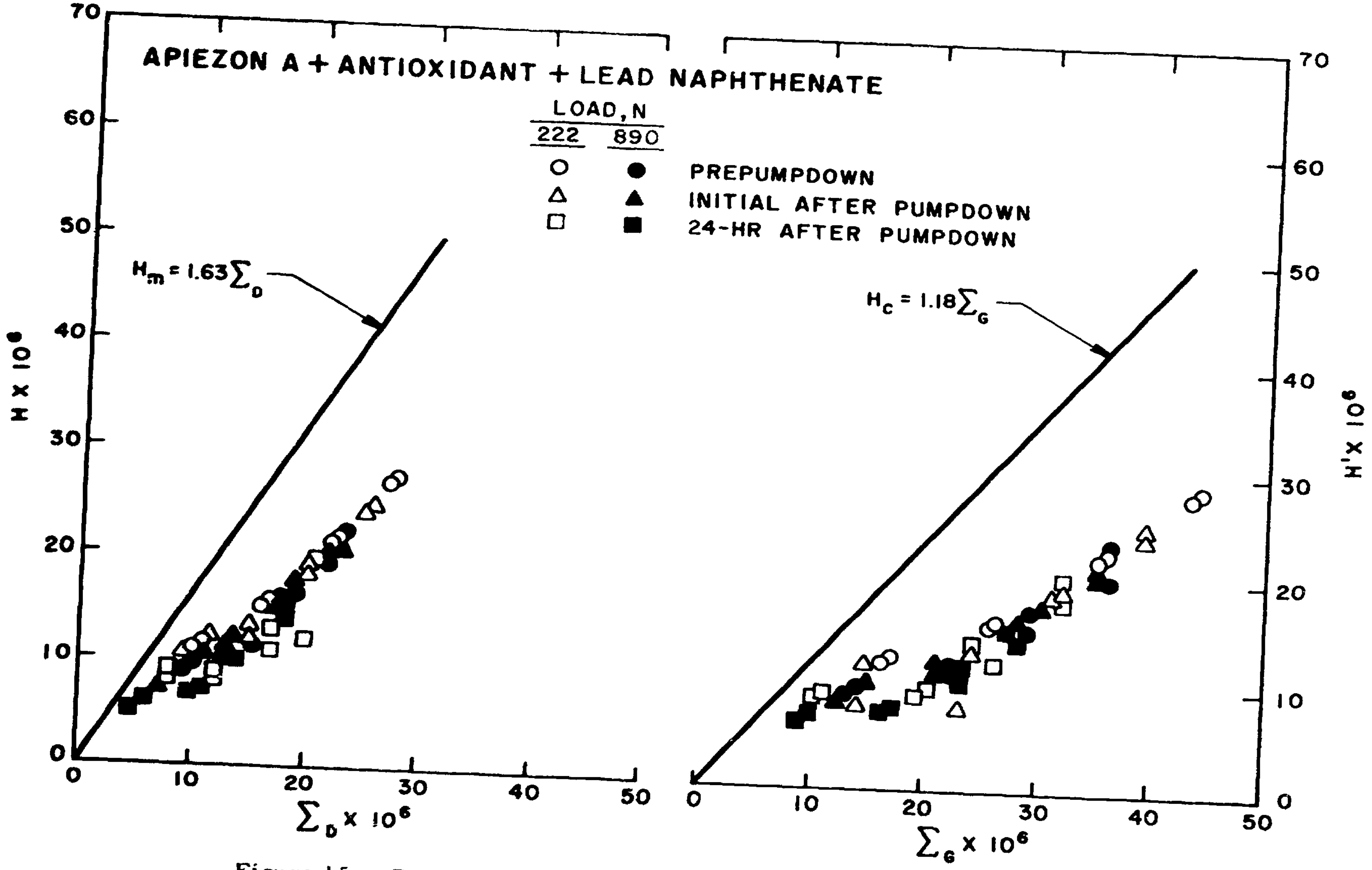


Figure 15. Dimensionless Oil Film Thicknesses for Standard Bearings Having Thick Initial Film of Low-Viscosity Oil

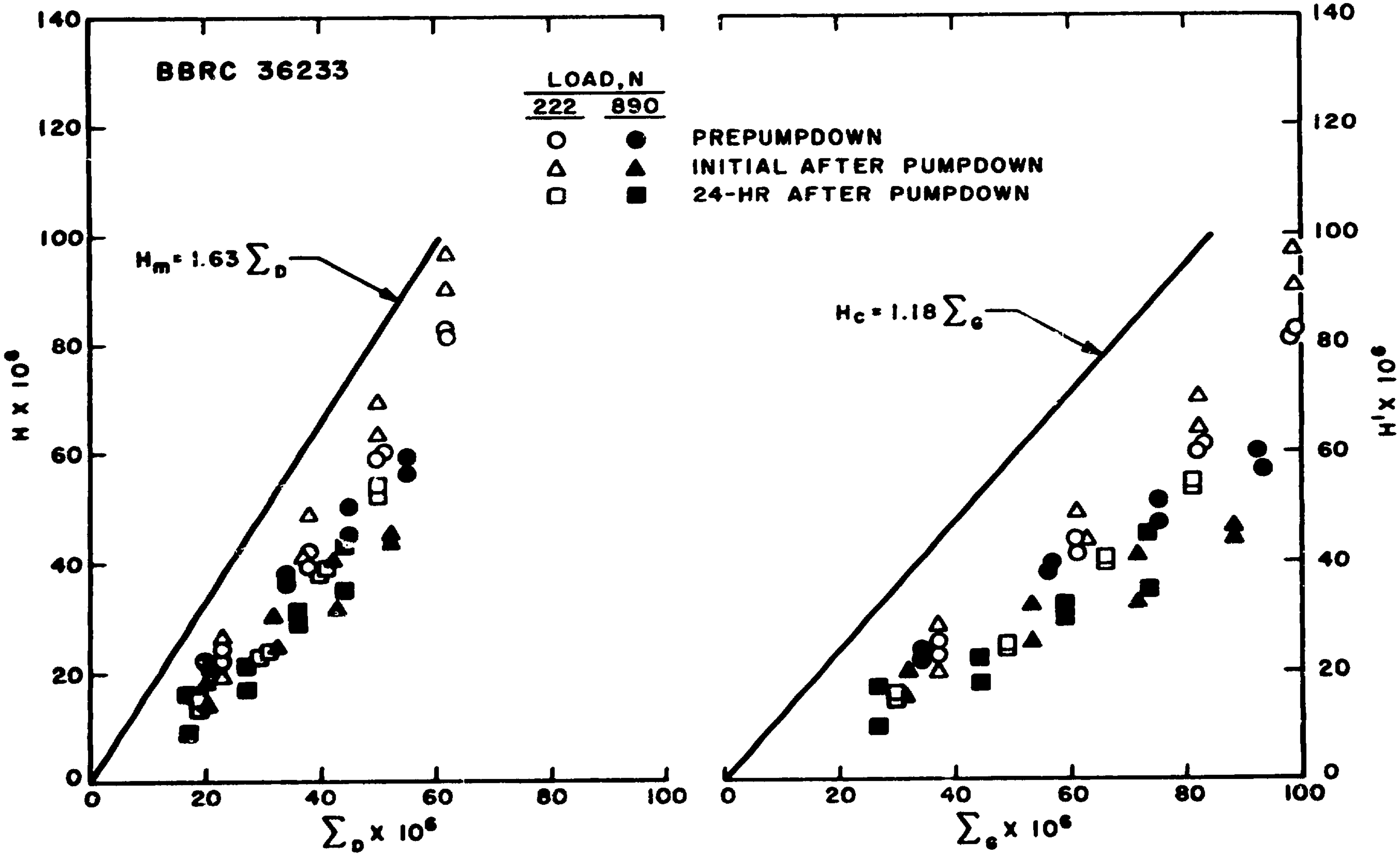


Figure 16. Dimensionless Oil Film Thicknesses for Standard Bearings Having Thick Initial Film of Intermediate-Viscosity Oil

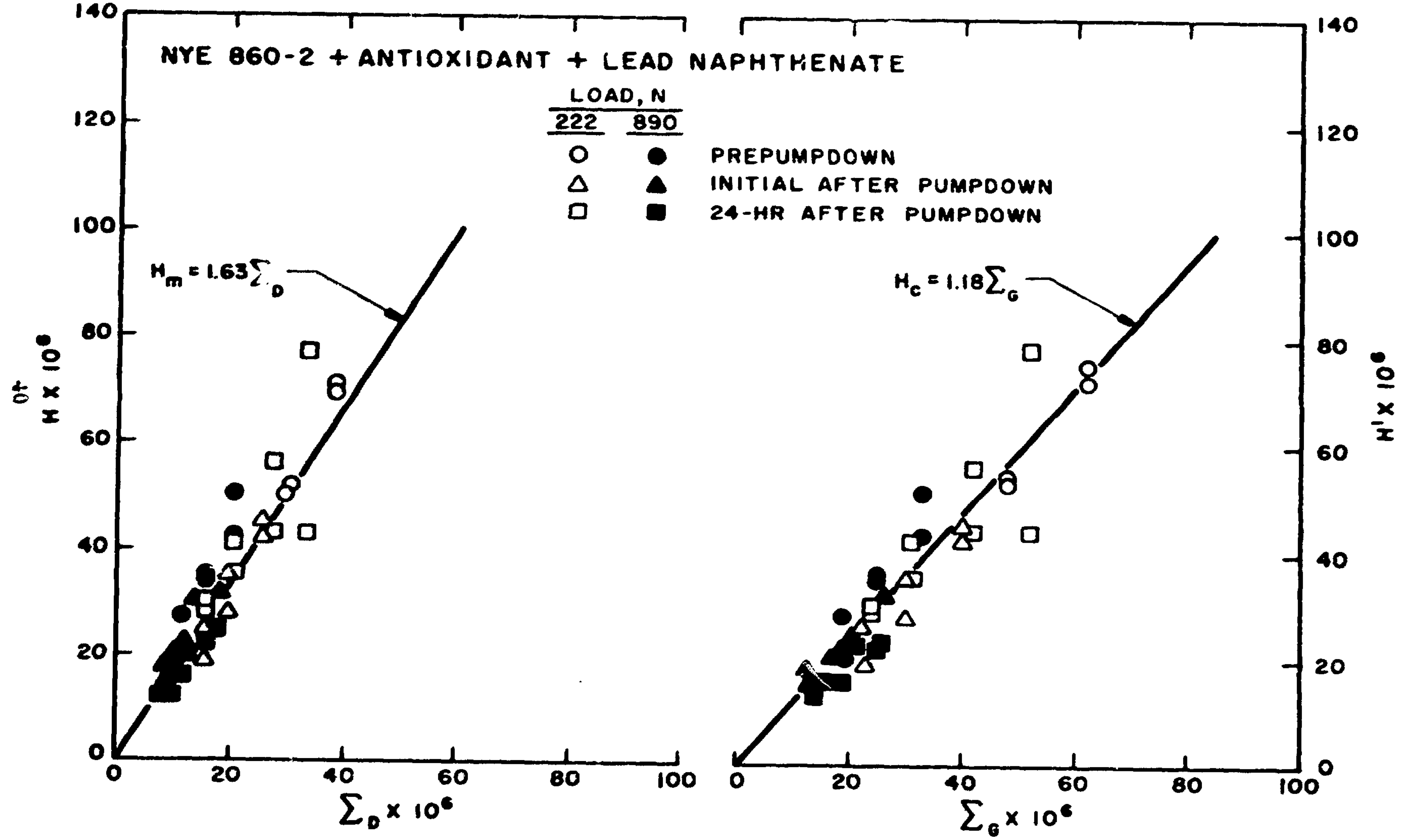


Figure 17. Dimensionless Oil Film Thicknesses for Standard Bearings Having Thick Initial Film of High-Viscosity Oil

in the table for Series II was conducted with the intermediate-viscosity oil, but with ZDP as the antiwear additive. As in Series I, the initial oil film thickness was the "thick film." The MRC standard bearings were employed for the tests in Series II.

Figures 16, 18, and 19 show a comparison of the experimentally-determined film thicknesses H and H' for each of these additives as compared to the Dowson Eq. (9) and the Grubin Eq. (8), respectively. In comparing these results it is seen that there appear to be load effects for the Apiezon C with ZDP. The low-load data clearly have larger dimensionless film thicknesses than the high-load data. On the other hand, this is not readily apparent for the Apiezon C with antioxidant or the BBRC 36233 (Apiezon C with antioxidant and lead naphthenate). If the best-fit line is drawn through each of these different formulations of Apiezon C, ignoring any load effects, the Apiezon C with ZDP would exhibit a slightly higher slope than Apiezon C with antioxidant, although not enough to be of major significance. In comparing these plots of data it appears that BBRC 36233 exhibits slightly thinner film thicknesses than the two other Apiezon oils with different additives, although the difference does not appear to be of major significance and may not be greater than the experimental error involved. Therefore, the effects of these additives on the formation of an EHD film, appear to be negligible for the particular test conditions employed in these tests.

Test Series III. In this test series the effect of the initial oil film thickness was studied. For both tests, the intermediate-viscosity oil with 1.5 percent antioxidant and 5 percent lead naphthenate (BBRC 36233) was used. Note in Table II that the first test is common to Series I, where the same initial oil film thickness with the same oil and standard test bearings were used, so that only one additional test was required in Series III. In the second test shown in the table for Series III, the initial oil film thickness was "thin film," which was about 1×10^{-4} mm, a less favorable condition for the development of full EHD oil films in the ball-raceway conjunctions. For this test, the MRC standard bearings were also used.

Figure 20 shows the dimensionless film thicknesses, H and H plotted versus Dowson's and Grubin's parameters, respectively for "thin film" bearings. As illustrated in the figure, there is clearly a load effect as shown by the data points for this test condition which is similar to, but, more clearly distinguishable than the one discussed above for Apiezon C with ZDP and having a thick initial oil film. The first conclusion, based on these data, is these "thin film" bearings did not have a sufficient amount of lubricant to maintain the EHD film thicknesses at the higher loads. On the other hand, there appeared to be a sufficient amount of lubricant to provide both central-region and minimum film thicknesses near those predicted by both Grubin's and Dowson's equations at the low load level. In comparing these data with the results shown in Figure 16 for the same lubricant but with a thick initial oil film, it is seen that the high-load results

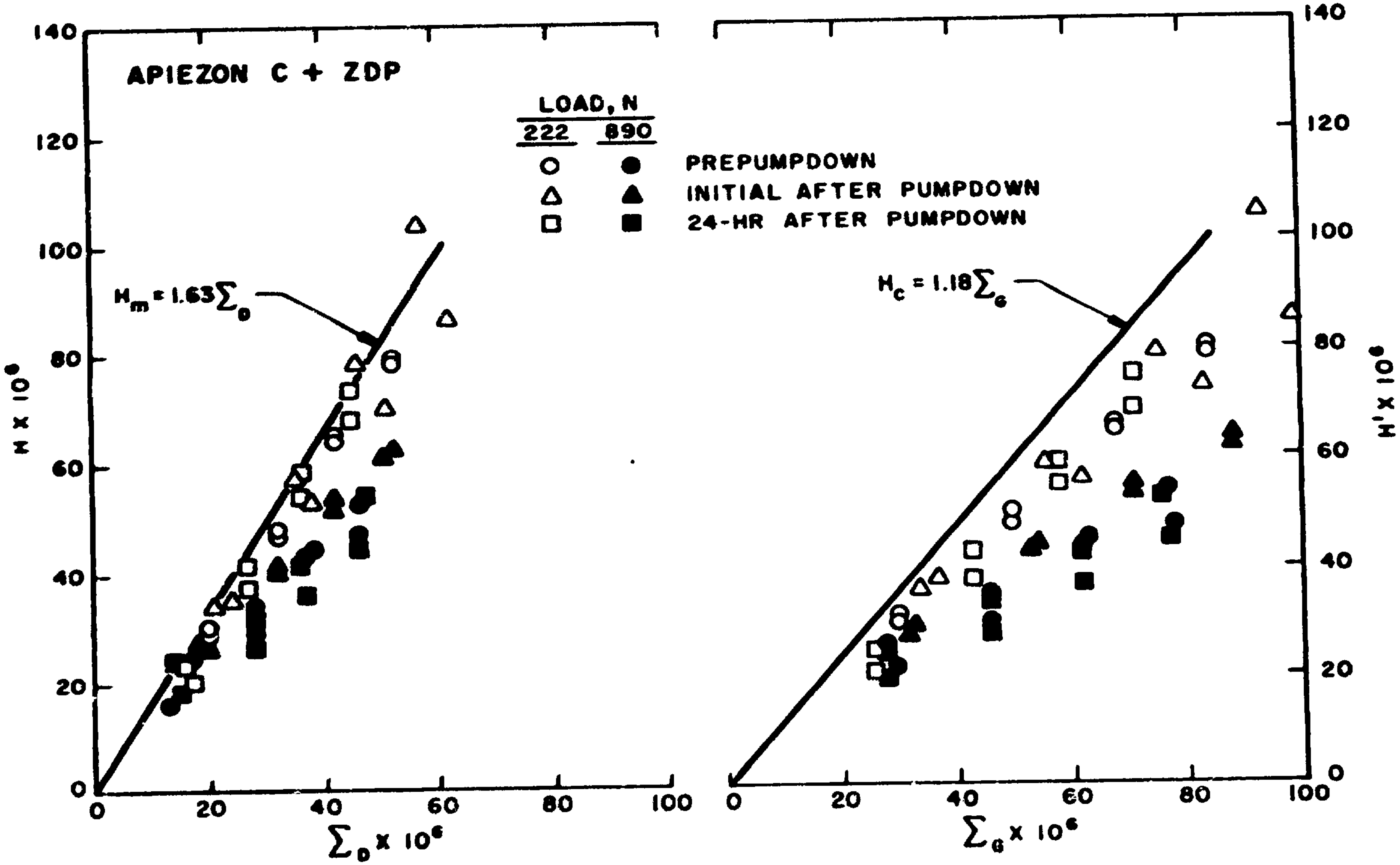


Figure 18. Dimensionless Oil Film Thicknesses for Standard Bearings Having Thick Initial Film of Intermediate-Viscosity Oil Containing Antiwear Additive ZDP

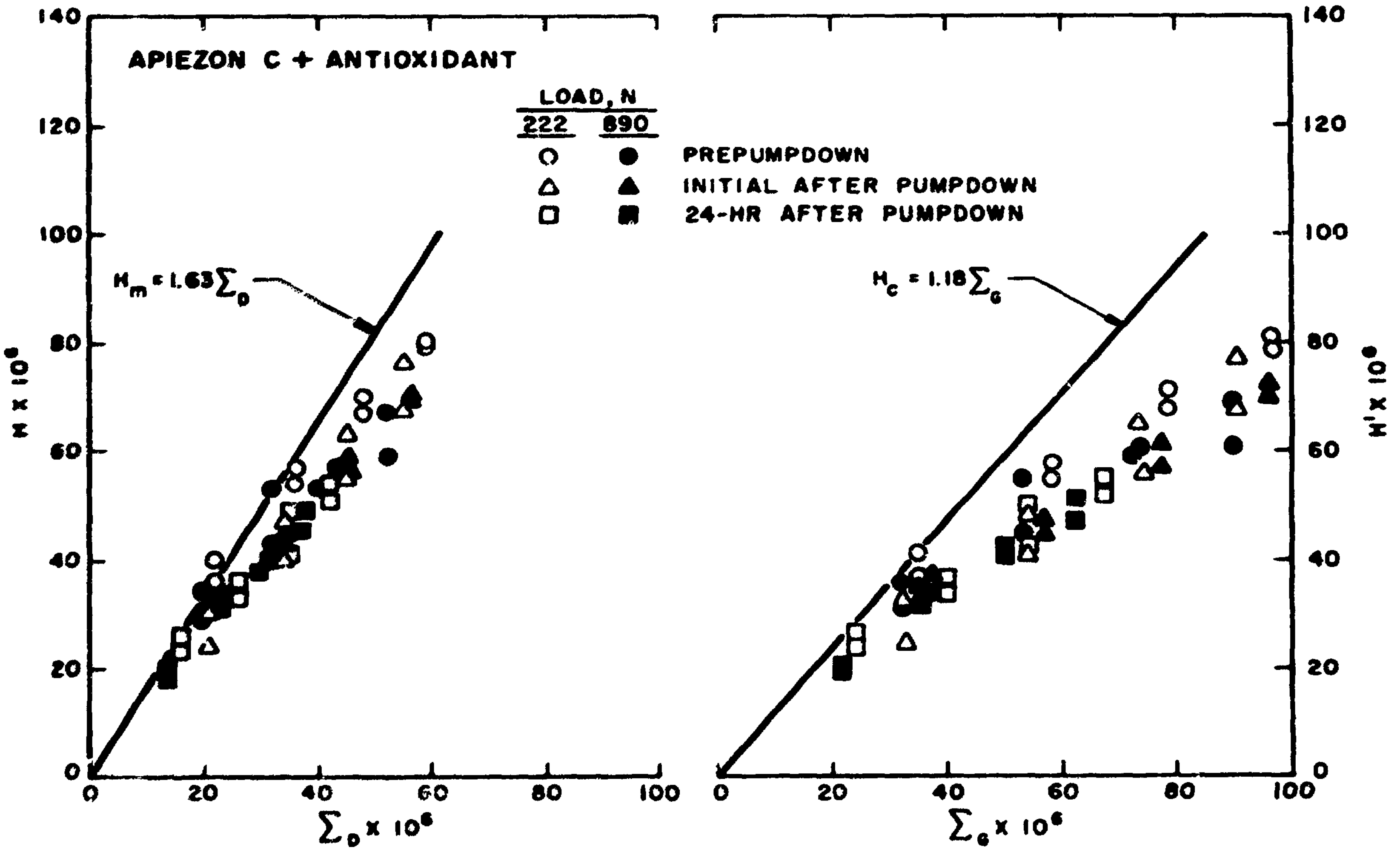


Figure 19. Dimensionless Oil Film Thicknesses for Standard Bearings Having Thick Initial Film of Intermediate-Viscosity Oil Containing No Antiwear Additive

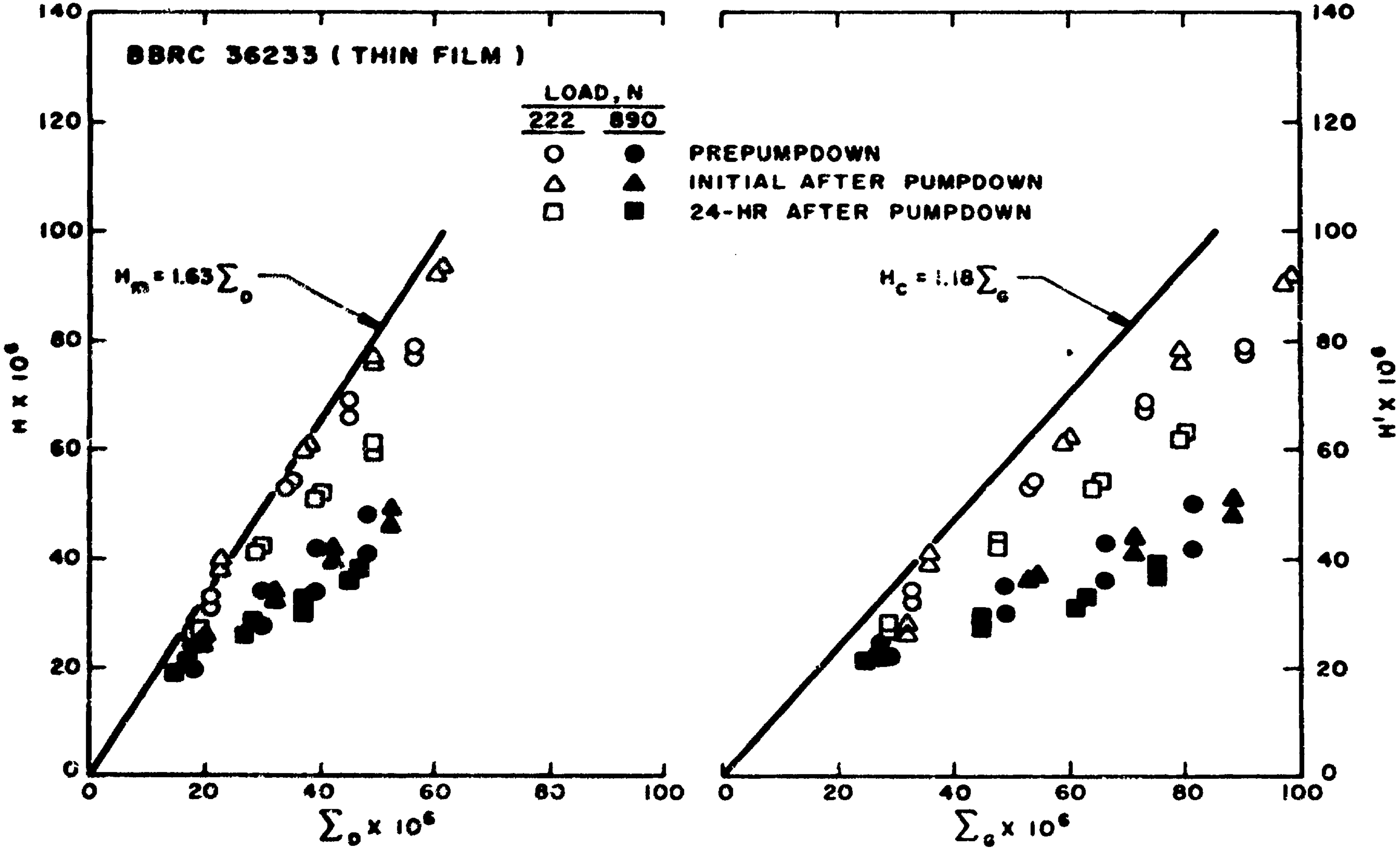


Figure 20. Dimensionless Oil Film Thicknesses for Standard Bearings Having Thin Initial Film of Intermediate-Viscosity Oil

for the "thin film" bearings (Fig. 20) agree very well with both the low-load and high-load results for the "thick film" bearings (Fig. 16). This suggests that possibly the low-load results for the "thin film" bearings are in error because of a testing load deficiency. Even if this is the case, both the "thick film" and "thin film" bearings appear to have film thicknesses sufficient to prevent asperity contact between the balls and races, but neither is performing in a flooded conjunction regime which should give experimental results in agreement with Dowson's and Grubin's equations. Again, these were short duration tests and the results might change considerably under extended operating conditions.

Test Series IV. This test series was conducted to determine the the effect of ball-race surface roughness on the oil film thicknesses in the EHD conjunctions in the bearing. This was done using the intermediate-viscosity oil with the additive package of 1.5 percent antioxidant and 5 percent lead naphthenate for all tests in the series. Tests were conducted with both "thick" and "thin" initial oil film thicknesses on the bearings, as shown in Table II. The data supplied by MRC and presented in Section II, Part II of this report showed the surface roughness of the rough bearing races to be 0.204 μm (8 μ in.) which is twice that shown for the standard bearings.

Figure 21 is for "thick" initial oil film with the BBRC 36233 additive package and rough ball-race surface roughness. Comparing this with Test Series I data for standard bearings lubricated with BBRC 36233 and shown in Figure 16 shows very good agreement and suggests that both the standard and rough bearings continue to operate with essentially the same film thicknesses. In fact the best-fit line drawn through both the H and H′ data on both these figures would show the rough bearings to have slightly thicker film thicknesses. Again, the best correlation appears to be between the measured data and Dowson's minimum film thickness equation.

The last two tests shown in Table II are for "thin" initial oil film with one test having been conducted with standard MRC bearings and discussed above under Test Series III. The previous data showed questionable load effects. The last of these tests was for bearings having the roughness doubled and a "thin" initial oil film and the results are shown in Figure 22. These data do not show the extreme load effect that is shown in Figure 20 except possibly the low-load, prepumpdown data. This observation further suggests that the low-load data shown in Figures 18 (discussed earlier) and 20 may be in error due to insufficient loading. Disregarding the low-load results shown in Figure 20, the measured film thickness data for both the "thin" initial oil film tests agree very well. Because the measured data is significantly less than either Dowson's or Grubin's predicted values it is probable that oil starvation in these "thin film" tests was present. On the other hand, even though a flooded conjunction apparently was not maintained, operation of the bearings appeared to be satisfactory with a minimum of asperity contact between the balls and races.

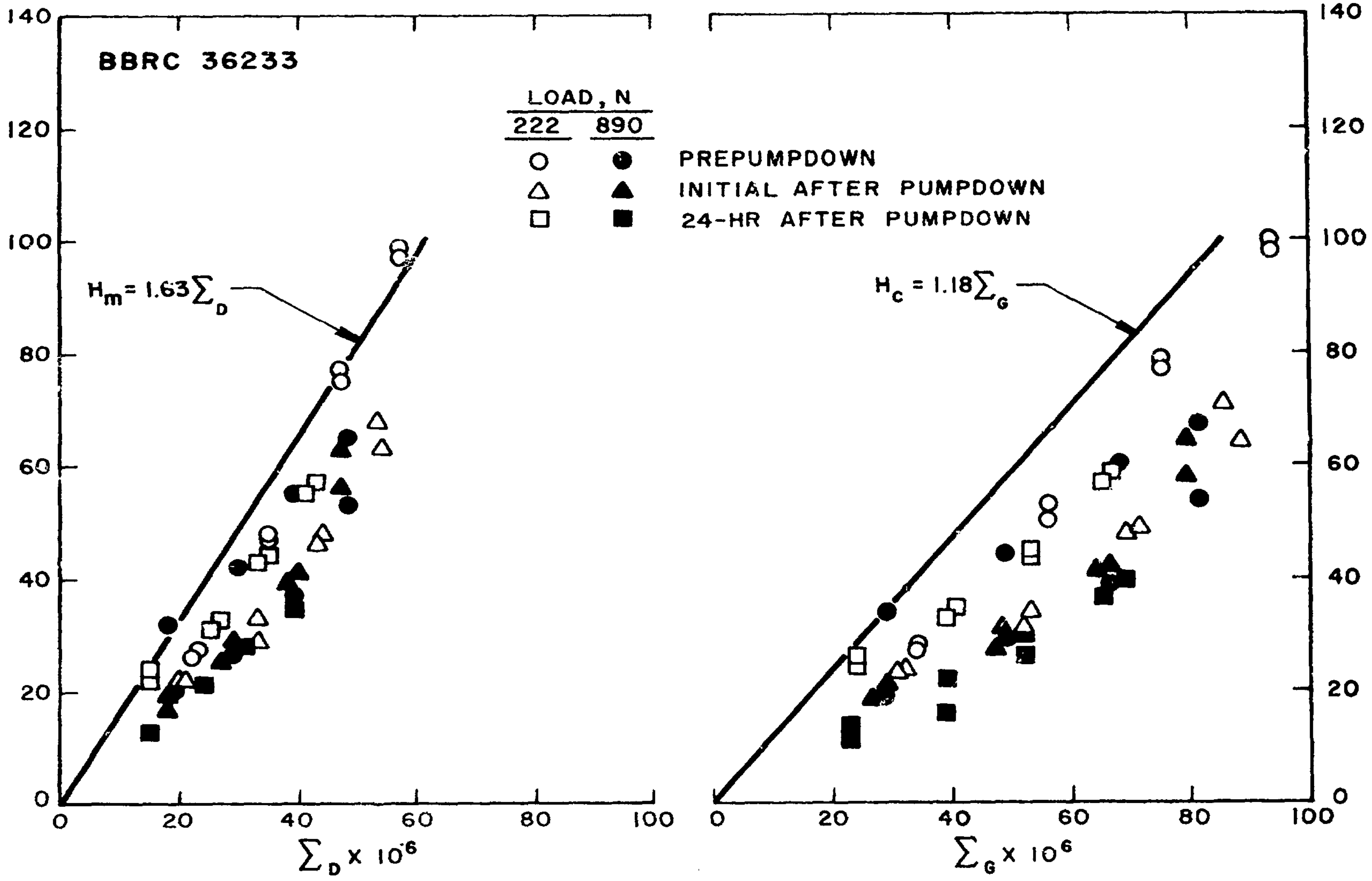


Figure 21. Dimensionless Oil Film Thicknesses for Rough Bearings Having Thick Initial Film of Intermediate-Viscosity Oil

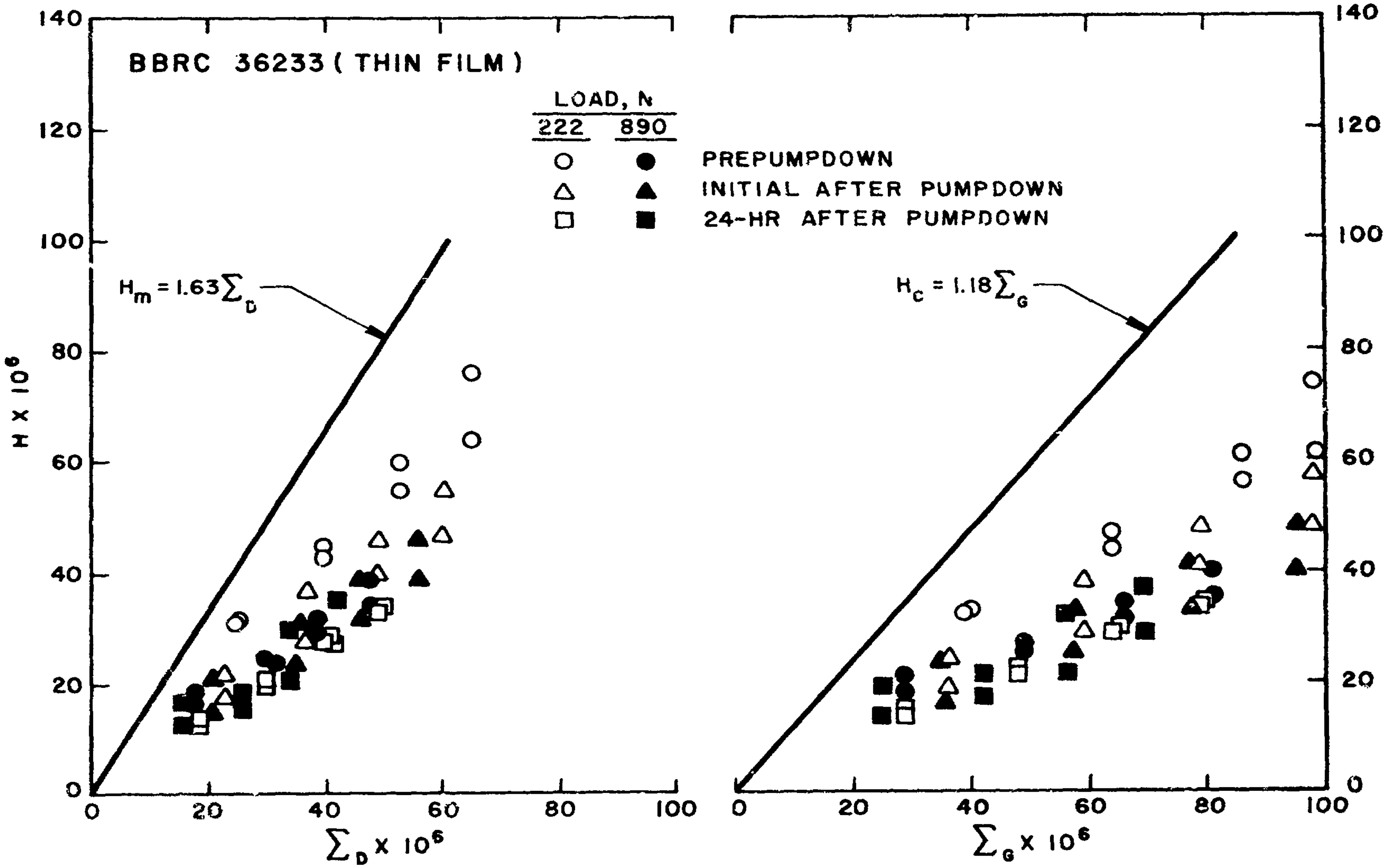


Figure 22. Dimensionless Oil Film Thicknesses for Rough Bearings Having Thin Initial Film of Intermediate-Viscosity Oil

Even though there are some discrepancies in these Task II data they do correlate well with both Dowson's and Grubin's dimensionless parameters giving much confidence in the race displacement measuring technique. Based on all of these Task II data it can be concluded that in general the film thicknesses H and H' calculated from ΔL_y measurements agreed better with Dowson's proposed minimum film thickness equation although in the case of the high-viscosity oil there appeared to be better correlation with Grubin's central-region film thickness equation. In reality it appears that the low-viscosity and medium-viscosity oils, whether the bearing be standard or rough and the initial oil film be "thick" or "thin", were operating in a slightly starved condition, but not severe enough to prevent proper operation or to cause wear or rubbing between the balls and races.

SECTION V

TASK III — ANALYSIS OF INFLUENCE OF LUBRICANT FILM THICKNESS ON BEARING LIFE EXPECTANCY IN A SIMULATED SPACE ENVIRONMENT

1. General

The purpose of this task is to provide a foundation for the development of accelerated tests, which can be used to predict bearing failure due to the loss or inadequate thickness of the EHD oil films.

As has been mentioned earlier in Part I of this report, in order to attain long bearing lives of the order of 10 to 15 years in space, it will be necessary to achieve intact EHD films in the ball-race conjunctions. This is because without full EHD films present, there will be surface contact, hence rubbing wear will occur.

Based on the test results obtained in Task II it appears that using the bearing race displacement technique for EHD film thickness measurement is valid and both Dowson's and Grubin's parameters correlate the data very well. In general, the calculated film thicknesses, using ΔLy measurements agree better with Dowson's Eq. (9). Both the low-viscosity and medium-viscosity oils, when applied to ABEC-7 bearings, had film thicknesses less than predicted by Dowson or Grubin indicating less than flooded conditions in the ball-race conjunctions. Also the "thin" initial oil film tests operating without reservoirs and using BBRC 36233 (medium viscosity) appeared to have oil film thicknesses very nearly the same as tests using "thick" initial oil films. Of course conclusions cannot be made for these same tests when extended for long durations under vacuum conditions. This task will attempt to provide some of this information.

It is believed that as far as failures due to loss or inadequate EHD film thickness are concerned, the most realistic way to conduct accelerated tests is through control of the Λ ratio. Accordingly, the Task III test program was designed to provide basic data on bearing failure due to the loss or inadequacy of the EHD film thickness, which it is believed will serve as a foundation for the development of accelerated tests.

Task III consisted of three long-duration bearing life tests run simultaneously. Each test was conducted in a test chamber identical to the one used in Task II, with two test bearings loaded against each other with a 890-N (200-lb) axial load. Bearing speed for all three tests was maintained constant at 100 rpm. Torque was monitored in all tests by the method described in Section II, Part I of this report.

The three separate test chambers were connected to the 1.2 m^3/s (1200 l/sec) vacuum pump, previously described in detail in Section II, Part I, and the bearing chamber pressure was approximately the equilibrium vapor pressure of the oil. Each chamber was provided with an LVDT identical to that used in Task II for measurement of the bearing film thicknesses.

A summary of these three tests is presented in Table III. As shown in the table, these tests were conducted at three different levels of Λ ratio designated simply as low, medium, and high, since at the time the tests were designed it was not known what the actual values would be. The three Λ levels would be obtained by varying the oil viscosity and the composite surface roughness of the ball-race combination. The low Λ value would be obtained using the Apiezon A oil with the rough bearings, the medium Λ value would be obtained using the same oil but in combination with the standard roughness bearing, and the high Λ value would be obtained using BBRC 36233 oil with the rough bearings. The Apiezon A oil would contain the standard additive package used in BBRC 36233. The degree of oil supply would be an initial thick film. Lubricant-impregnated reservoirs would also be installed in the bearing test chamber. Using values of 0.102 μm (4 μin.) and 0.204 μm (8 μin.), as supplied by MRC and given in Section II, Part II of this report, for the standard and rough bearing race surface finishes in the transverse direction (across grinding marks), respectively, and a ball surface finish of 0.025 μm (1 μin.), and employing the expression for composite surface roughness, δ_c, given in Section III, Part I, values of approximately 0.10 μm (4 μin.) and 0.18 μm (7 μin.) are obtained for δ_c. This assumes the bearing race surface finish in the direction of the grinding marks is one-half that in the transverse direction. Then using experimental values of film thicknesses as calculated from ΔLy for the two tests using Apiezon A with antioxidant and lead naphthenate, and one test using BBRC 36233 and employing the following equation:

$$\Lambda_m = \frac{h}{\delta_c} \tag{11}$$

where Λ_m = dimensionless minimum oil film thickness ratio

h = oil film thickness calculated using Eq. (38), Appendix I

δ_c = composite surface roughness of two bearing surfaces

values of 0.71, 1.25, and 1.43 are obtained for Λ_m for the low viscosity oil and rough bearings, low viscosity oil and standard bearings, and medium viscosity oil and rough bearings, respectively, as shown in Table III. The film thickness values used in calculating the above Λ_m values were approximate average values that were obtained at the end of the long-duration tests and will be presented in the next subsection of this report under experimental results.

TABLE 3. SUMMARY OF TASK III TESTS

Test No.	Variable Studied	Viscosity at 25 C (77 F), $m^2/s \times 10^6$	Initial Film Thickness	Ball-Race Surface Roughness
1	Low Λ	54	Thick	Roughness doubled
2	Medium Λ	54	Thick	MRC standard
3	High Λ	225	Thick	Roughness doubled

TEST CONDITIONS:

Pressure = equilibrium vapor pressure of test oil
Temperature ≈ 25 C (77 F)
Load = 890 N (200 lb)
Speed = 100 rpm

OIL DESCRIPTION:

Medium viscosity oil = BBRC 36233
Low viscosity oil = Apiezon A + 1.5% Antioxidant + 5% Lead naphthenate

2. Presentation of Experimental Results from Long-Duration Bearing Tests

The computer program that was developed and discussed in Section IV, Part II of this report was modified to accommodate these Task III measurements. A listing of the modified computer program is shown in Appendix IV and the tables of computed data for the long-duration bearing tests are presented in Appendix V.

Figures 23, 24, and 25 show the measured variables for the three long-duration Task III tests as a function of time. The film thickness data points are values that were calculated from the measured displacements, ΔLy. For these Task III tests the aft bearing-inner race contact data were plotted rather than the aft bearing-outer race contact data that were selected for plotting in the Task II tests. This was done because these inner race contact data are printed out in the Task III tables (Appendix V) whereas only the equations containing the geometric constant are given in these tables for computing the outer contact film thickness values. Again as explained in Section IV, Part II, the four different conjunction films for each test condition at any particular time are calculated from a single displacement measurement, ΔLy. The solid lines shown on the plots of H' and H versus time in Figures 23, 24, and 25 are the values that would be obtained using Grubin's Eq. (8) and Dowson's Eq. (9) for calculating central-region and minimum dimensionless film thicknesses, respectively, at the measured bearing temperatures. When comparing the data calculated from measured ΔLy values with these empirical values from the equations, it is seen that the actual film thicknesses in the bearings, for the different Λ_m ratios, are in general less than both the empirical minimum and central-region values predicted by the equations. This agrees with the Task II data presented in the previous section of this report and again suggests less than flooded lubrication in the ball-race conjunctions. It is worthy to note that the low Λ_m test (low viscosity oil with rough bearings) displayed very small film thicknesses throughout much of the first few hundred hours of testing, but they increased until agreeing very well with Dowson's minimum film thickness equation for the last portion of the test. On the other hand, the medium and high Λ_m tests displayed film thicknesses that increased to values close to those predicted by Dowson early during testing and remained fairly constant throughout the remainder of the tests. It is also of interest to note that at several times the measured values behaved as would be predicted when there were bearing temperature increases or decreases. For example, note the increase in measured and calculated film thickness in Figure 25 at about 1200 hours. Some of the bearing temperature changes were caused by changes in the laboratory temperature because of air conditioning failure. Some of the temperature changes were also caused by the test rig speed changing, but several of the bearing temperature changes cannot be explained.

Vacuum in the chamber seemed to behave as would be expected, with

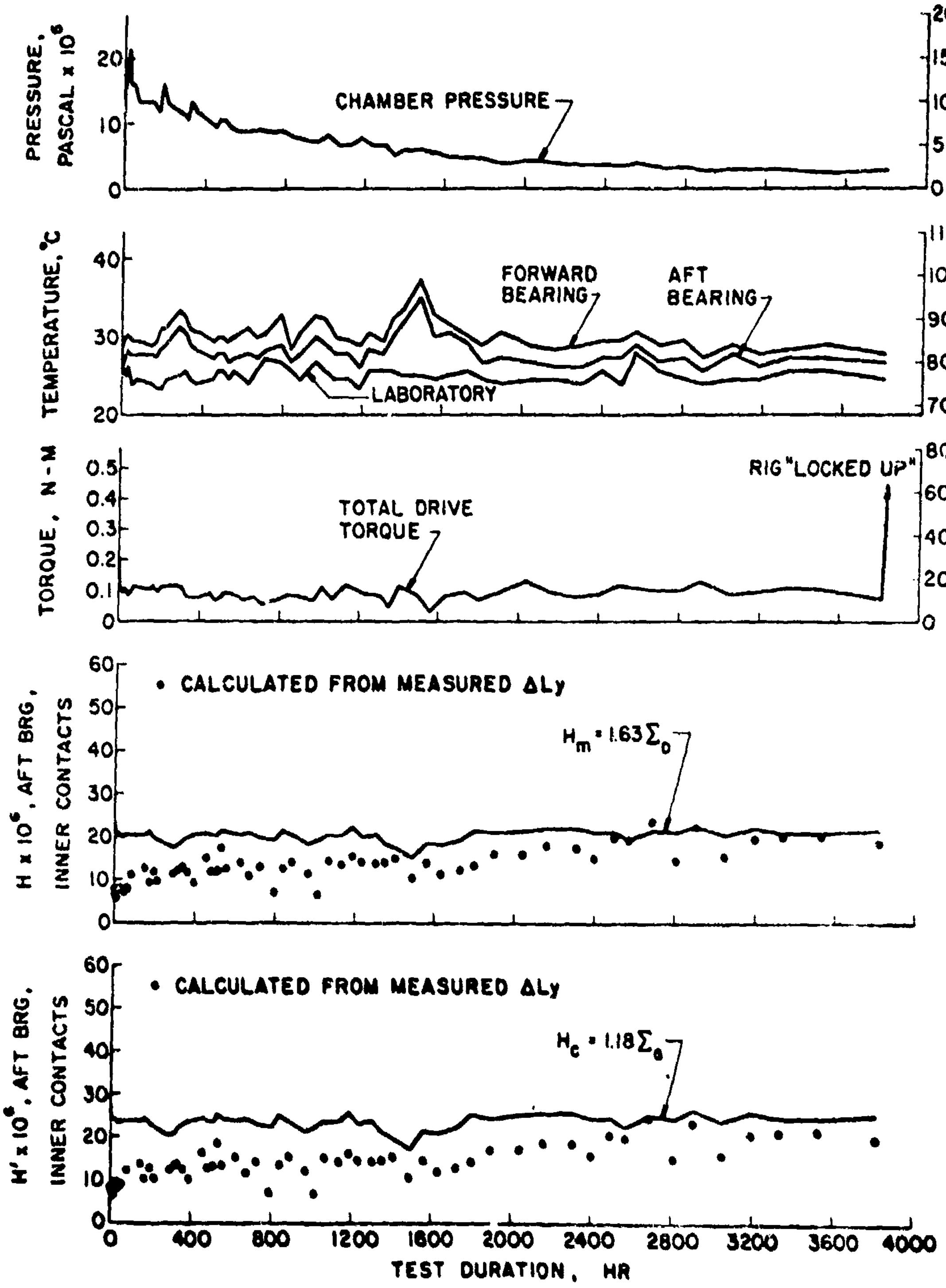


Figure 23. Measured Variables for Endurance Test Using DMA Bearings Lubricated with Thick Initial Oil Film of Apiezon A and Having Low Λ_m

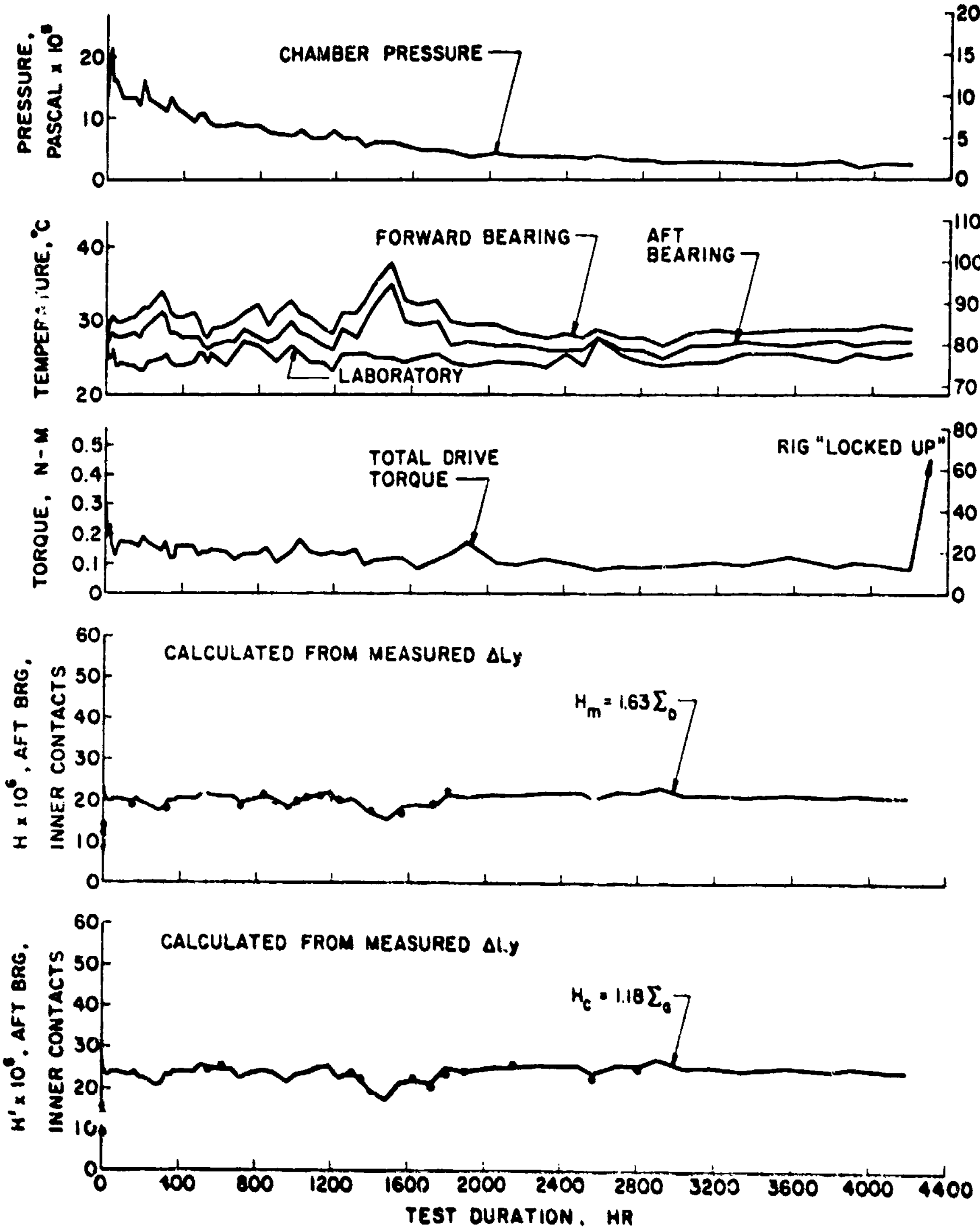


Figure 24. Measured Variables for Endurance Test Using DMA Bearings Lubricated with Thick Initial Oil Film of Apiezon A and Having Medium Λ_m

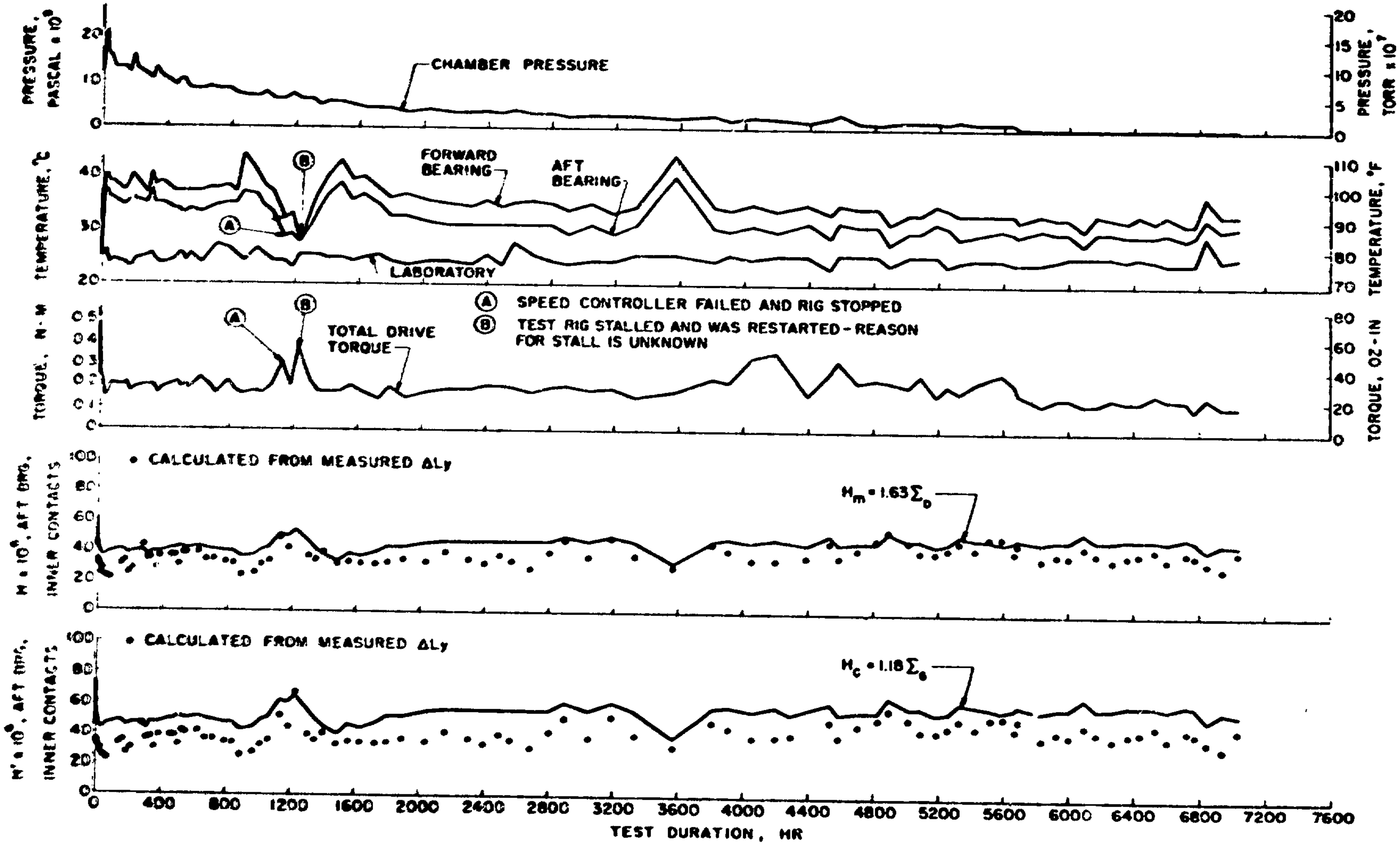


Figure 25. Measured Variables for Endurance Test Using DMA Bearings Lubricated with Thick Initial Oil Film of BBRC 36233 and Having High Λ_m

the pressure first increasing when the test rigs were initially put into motion and then continuing a gradual decreasing trend until the end of the program. The measured torque in the test bearings appeared to behave normally with some periodic fluctuations that can probably be attributed to the cage rubbing against the outer race in the test bearings. This will be discussed in more detail later in the report. The Test No. 1 and Test No. 2 bearings, both tests using formulations of Apiezon A oil, "locked up" within 500 hours of each other; Test No. 1 ran 3836 hours and Test No. 2 ran 4294 hours. What may be of significance is that both of these tests did employ the low-viscosity Apiezon A and did fail after similar test durations even though the Λ_m of one was 1.76 times the other and both were less than 2.0. For both tests, it appears that the oil may have been wiped from the cages at the ball-cage conjunctions and was not replenished by the oil impregnated cages or reservoirs, thus causing dry rubbing wear and eventual "lock up." This will be discussed in more detail later in the report. Upon "lock up" the bearings in these test rigs could not be freed by turning the outer magnets either backward or forward. The maximum torque capability of the driving magnetic couplings was approximately 0.63 N-m (90 oz-in.), therefore, a large amount of torque could not be applied until disassembly of the bearing rigs. It should be noted that the bearings in Test No. 2 started making an unusual noise after approximately 3336 hours of operation. Nothing unusual was observed in the measured data at this time. The noise sounded similar to moving parts rubbing against each other and continued until the end of the test. One ΔLy measurement, taken at 3816 hours, for this Test No. 2 was obviously too great, as is shown in Figure 24.

Removal and Inspection of Two Failed Task III Bearing Rig Assemblies. Approximately 1350 hours after the bearings in Test No. 2 "locked up" and 1850 hours after the bearings in Test No. 1 "locked up", at the request of the AFML project engineers, the following procedure was undertaken.

a. Leave the bearing assembly with the BBRC 36233 oil running throughout the removal of the two other bearing assemblies from vacuum system.

b. Using nitrogen, bring the chamber pressure to slightly above atmospheric, and maintain a small positive pressure differential as the bearing assemblies are removed, to prevent room air from entering the vacuum chamber.

c. Cover the end of each bearing assembly with aluminum foil as it is removed from the vacuum chamber.

d. After each bearing assembly is removed from the vacuum chamber, attach a cover plate to the port.

e. When both bearing assemblies have been removed and the cover plates are in place, put the system under vacuum again.

f. Select one of the bearing assemblies, and carefully extract the inner housing from the outer bearing rig chamber.

g. With the inner housing fixed, and using a suitable torque wrench, apply torque to the nut holding the magnets on the shaft. Be sure that the torque is applied in the direction that the bearings rotated in the test. Gradually increase the torque until the slightest motion is observed and record this breakaway torque.

h. Remove the load in steps of 222 N (50 lb), and after each load change repeat step g above.

i. When all the load has been removed, reapply the 890 N (200 lb) load and see if the bearing is locked up again.

j. Carefully dismantle the bearing assembly and remove the bearings. Use gloves and laminar flow hood during the disassembly. When the bearings are removed, wrap them in aluminum foil for temporary storage.

k. Under the laminar flow hood and using gloves, dismantle each bearing.

l. Weigh the retainers and reservoirs and record these weights.

m. Inspect the balls and races of each bearing for wear tracks, etc., and record findings.

n. Inspect the retainers for wear and record findings.

o. If the bearing components have to be cleaned for any reason during the inspection process, use heptane, save it, and send it to AFML.

p. After the inspections are complete, reassemble each bearing, wrap in aluminum foil, label and store.

q. Repeat steps f through p for the other bearing assembly.

The rig from Test No. 1 was selected first for the above procedure. Upon removing the inner housing from the bearing rig chamber (step f) it was evident that the cage was pushed against the inner land of the outer race of the aft bearing on one side while displaying a gap at the opposite side. This is illustrated in the photograph shown in Figure 26. Also observed was an ample amount of oil in and around the bearing. The oil appeared to be darker than when first installed in the test rig at the beginning of the test.

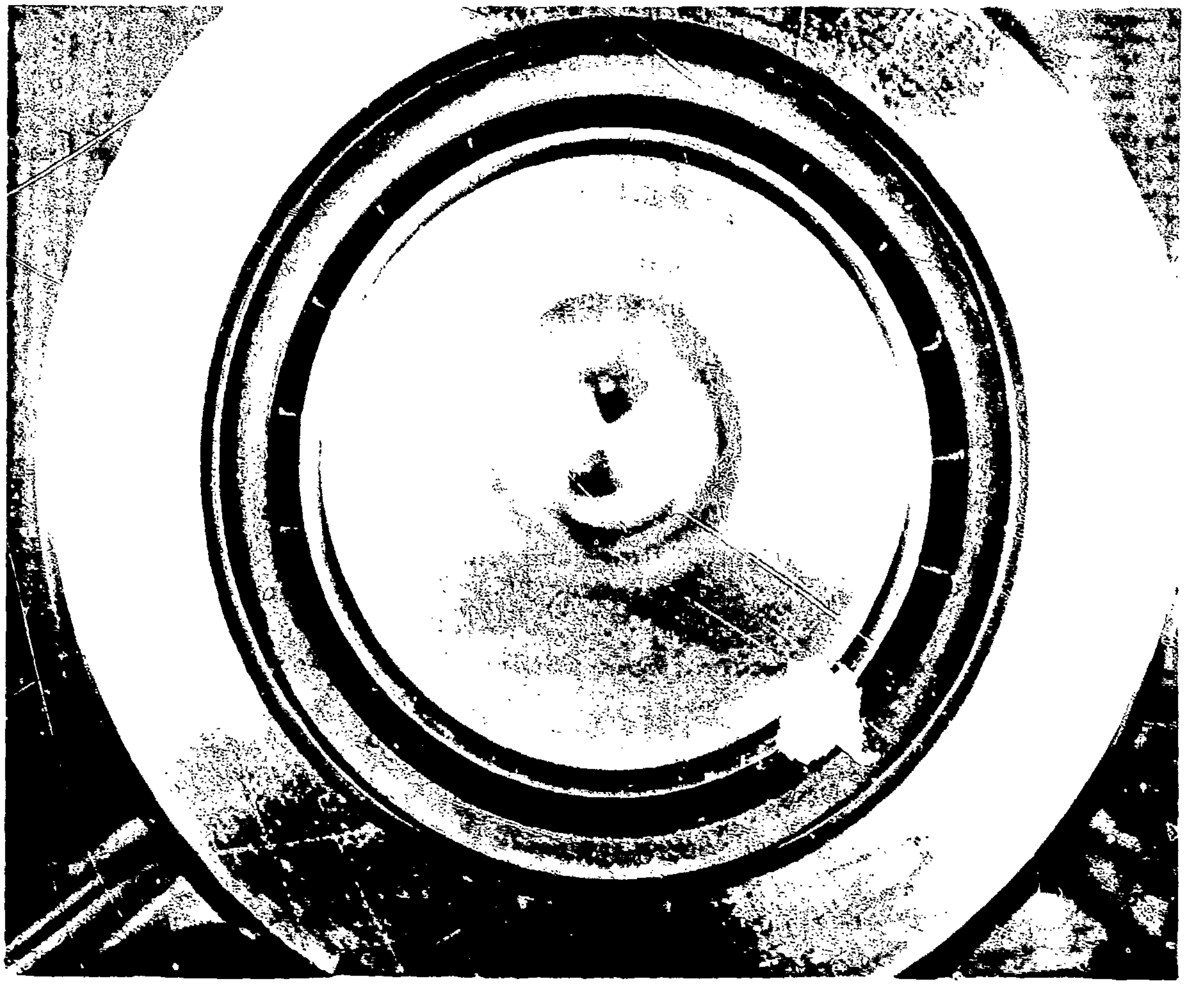


Figure 26. View of Wedged Cage After Endurance Test "Lock Up"

Torque measurements were made as outlined in step g above and the results were as follows:

1. Initial full load breakaway (step g) = 0.70 N-m (99.7 oz-in.)

2. Second 667 N (150-lb) load torque measurement (step h) = 0.43 N-m (61.0 oz-in.)

The bearing became relatively free at this time, therefore, it was reloaded to 890-N (200-lb) axial load and similar torque measurements were taken giving an average value of 0.071 N-m (10.0 oz-in.). Again the axial load was reduced to 667 N (150 lb) and repeat measurements of torque gave an average value of 0.018 N-m (2.6 oz-in.). At this time the bearings appeared to be completely free and the cage had moved away from the inner land of the outer race seeking a more concentric position. At this time the axial load of 890 N (200 lb) was reapplied and the inner housing placed back in the bearing rig chamber. Instrumentation was again installed and the rig was attached to the Task II vacuum system. Bearing displacement and torque measurements were made both in air prior to pumpdown and after evacuation of the test chamber. These appeared to be somewhat higher than normal, but, the bearings would operate. There was an unusual noise (chatter) in the bearings above approximately 60 rpm. After running approximately 24 hours the test was stopped because the rig was found stalled, but the bearings were not "locked up." The cause of the stall is not known. The rig was completely disassembled. Photographs and observations were made during disassembly and these will be discussed later.

At this time the rig from Test No. 2 was disassembled. Again, when the inner housing of the rig was removed from the bearing rig chamber (step f above) it was noted that the cage was pushed against the inner land of the outer race of the aft bearing on one side while displaying a gap at the opposite side. A small pool of oil was present at the bottom of the inner housing in front of the loading diaphragm. Oil could also be seen around the ball-inner race contacts. Prior to proceeding through the disassembly procedure given above for determining "breakaway" torque of the bearings it was decided to attempt to push the bearing cage to a central position. Since the cage was securely wedged between the outer race and the balls, it required gradually moving the cage to a more central position by prying with a screwdriver between the cage and inner race at several locations. This was carefully done, and once the cage moved away from the inner land of the outer race the bearing movement became free and easy. Average torque required to rotate the bearings after this "freeing" manuever was 0.082 N-m (11.6 oz-in.) which indicated extremely free bearings in the rig. It should be noted that in both cases of "locked up" bearing rigs, it appeared that the aft bearings had stalled because of wedging between the cages and the outer races. At this time the Test No. 2 rig was completely disassembled. Photographs and observations of both the failed ("locked up") bearings will be presented and discussed at this time.

Highlights of Task III Failed Bearings. Figures 27 and 28 show a close-up view of the ball track on the outer and inner races of the forward bearing in Test No. 2. As seen in these photographs there was an appreciable amount of dark debris collected on both sides of the ball track. The three other bearings employed in these two tests showed somewhat less of this debris. Close inspection of the outer land surface of the phenolic cages for the four test bearings showed that the bearing having the most debris on the inner and outer races also had the most rubbing wear on the phenolic cage. In other words, the amount of rubbing wear on the outer land or surface of the cage appeared to be directly related to the amount of dark debris deposited along the ball tracks on the bearing races. This material was easily removed from the race surfaces by wiping with a clean cloth or paper tissue. Figure 29 illustrates a flake of debris deposited in the ball pocket of the Test No. 2 forward bearing. All four of the bearings used in these two tests displayed some of these shiny flakes of debris in the ball pockets, although, they appeared to be larger in the two bearings used in Test No. 2. Also shown in Figure 29 are the darkened wear tracks on the outer land surface near the ball pockets of the phenolic cage. Seemingly, these wear tracks were deeper and more noticeable near the ball pockets that contained flakes of wear debris. Apparently these flakes are composed of wear material that has been removed from the cages.

Post-test inspection of the ball surfaces revealed a film of oil remaining intact with no visible wear track, pitting, or flaking. After wiping the debris from the race surfaces, they were found to be bright and shiny showing no evidence of pitting or extreme wear.

Figure 30 shows four of the oil-impregnated reservoirs that were removed from one of the rigs used in Task III tests. These reservoirs appeared very much as they did when installed in the test rigs. They were very brittle and extreme care had to be exercised to keep from breaking small pieces from the reservoirs during assembly or disassembly. Before and after weight measurements showed that the average oil weight loss for these reservoirs was only 1.4 and 2.2 percent during these two failed Task III tests.

Based on the test results and observations obtained during Task III, it can be concluded that the bearing lubricated with Apiezon A and having a low and medium Λ_m did not fail because of insufficient EHD lubrication at the ball-race conjunctions. Instead it appeared that the failures were caused by torque increases that were due to wedging of the cages between the balls and outer races. This indicates either a poor design of the bearing cages or poor lubrication between the cage and the balls and between the cage and the outer race lands of the bearing. Inspection of the failed bearings led to the conclusion that the contacting surfaces between the balls and cages would become "dried out" because of poor cage lubricant feed. Once this happened, wear of the cage in the ball pockets would be initiated and continue

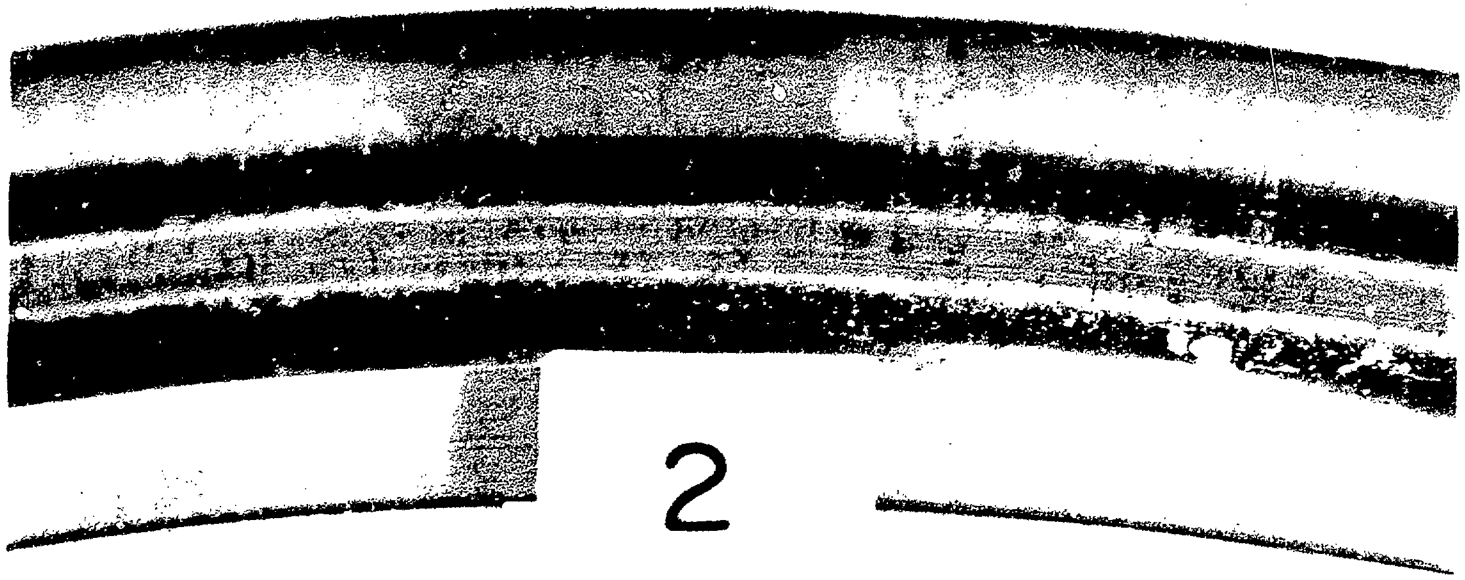


Figure 27. Ball Track in Outer Race of Forward Bearing

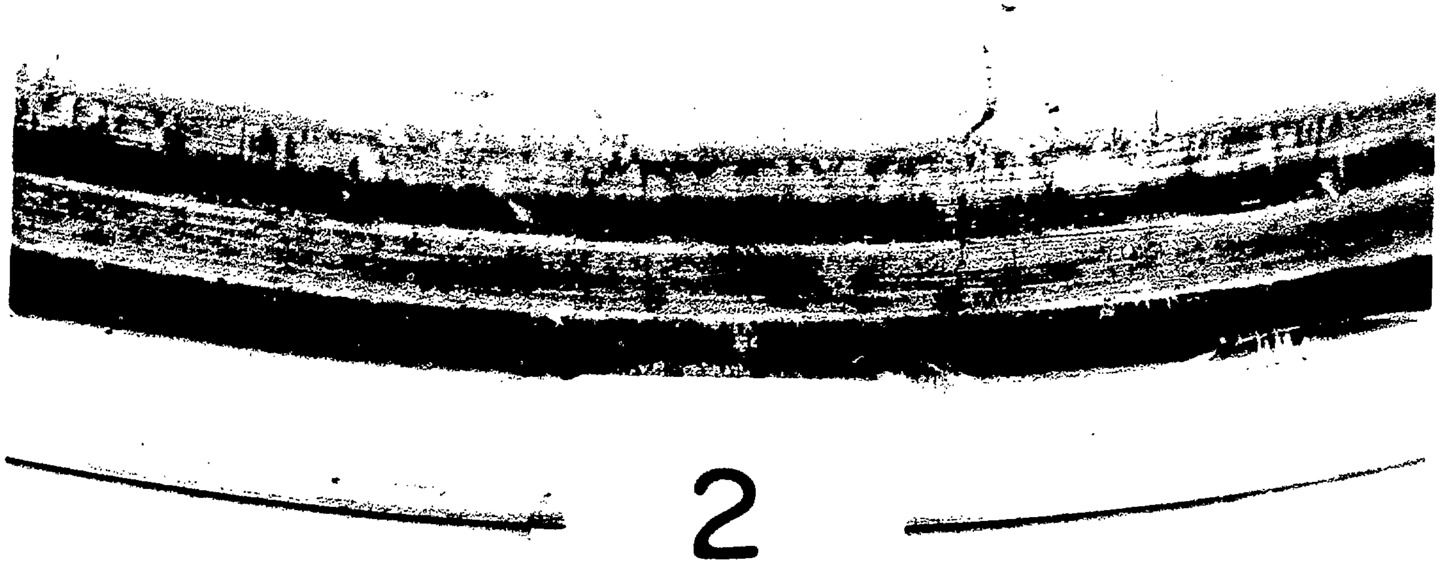


Figure 28. Ball Track in Inner Race of Forward Bearing

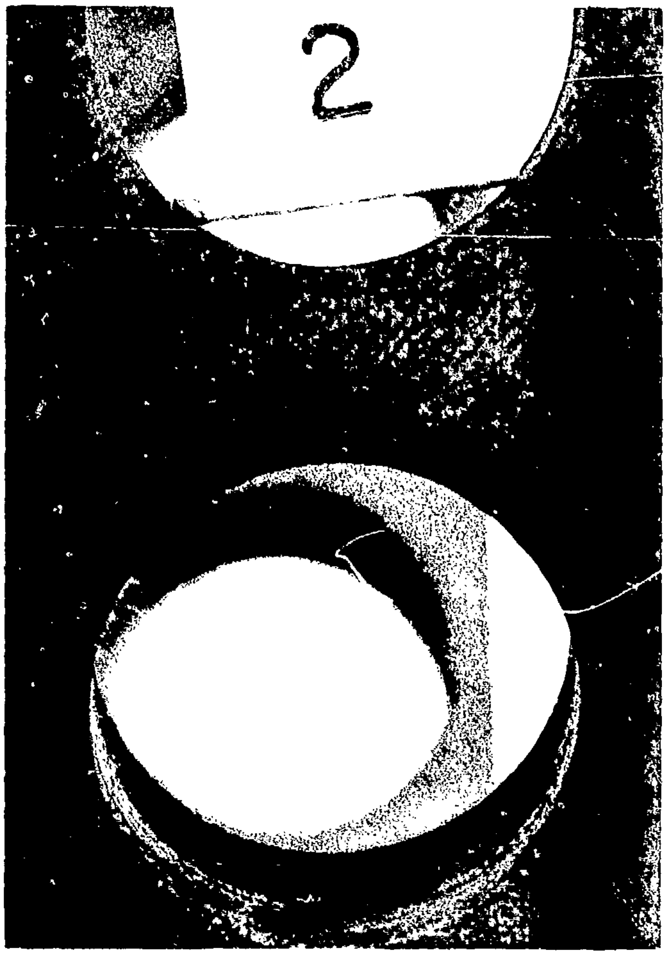


Figure 29. Flake of Debris Deposited in Ball Pocket of Forward Bearing Cage

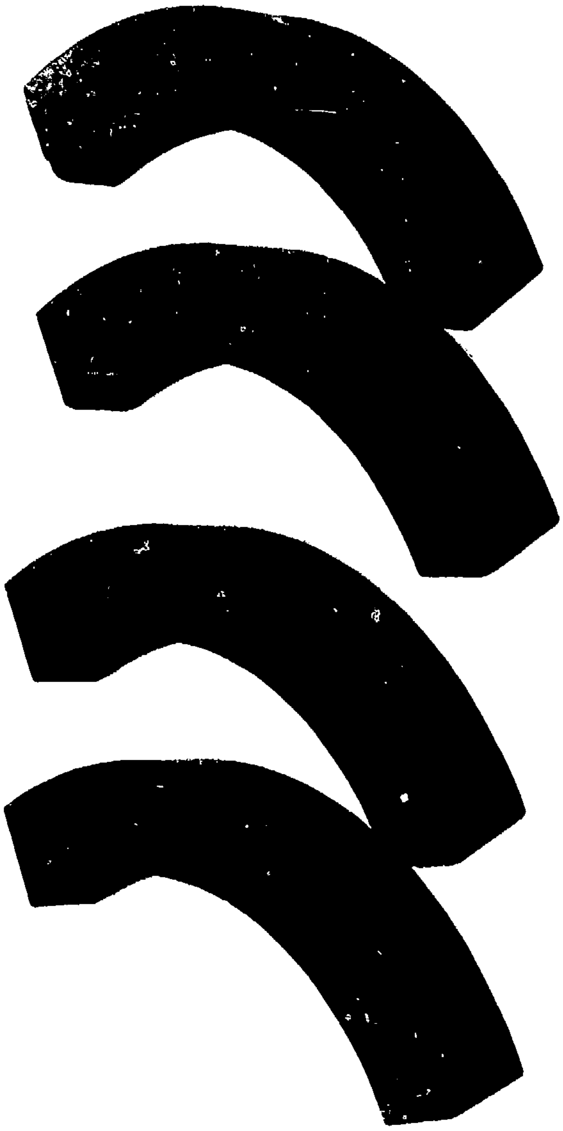


Figure 30. Four Oil-Impregnated Reservoirs as Removed from Test Rig

to propagate as is shown in Figure 29. Simultaneously, due to increased friction between the balls and cage, the cage would be pushed against the lands of the outer race of the bearing with additional forces. Due to these larger forces and additional wear the bearings would soon reach the point where "lock up" occurred because of insufficient driving torque.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions

Task I. From the results of the optical interference measurements of the EHD film thicknesses for the various oils employed in this study, it is concluded that the special test oils formulated for vacuum use behave in general in the same manner as do ordinary straight mineral oils. This was shown in Section III in Figures 9 and 13. The results shown in these figures emphasize the fact that when optically-measured EHD film thickness data for different oils are compared, the data should be obtained under identical operating conditions. That is, due to thermal effects in the conjunction inlet region, EHD film thickness data obtained under pure sliding conditions should not be compared with those obtained in pure rolling, except at very low values of the dimensionless correlating parameters Σ_c and Σ_m. As Σ_c and Σ_m increase, the difference between the EHD film thickness for pure rolling and pure sliding becomes greater.

From these optical measurements it is also concluded that even for flooded conjunction inlet conditions, the linear relationships between H_c versus Σ_c and H_m versus Σ_m, as proposed by the correlating equation of Archard(3) and Cameron,(4) break down as Σ_c and Σ_m are increased. It is believed that the nonlinear trend is due to thermal effects, and apparently not influenced by the oil composition as long as operation is in the full EHD regime.

Task II. From the EHD film thickness measurements made for the DMA bearings using the race displacement technique, a number of conclusions may be drawn. Taking any individual figure among Figures 14 through 22, it is concluded that the dimensionless parameters Σ_D and Σ_G correlate the EHD film thicknesses calculated from the measured race displacement reasonably well. For any given oil there is a unique and approximately linear relationship between H and Σ_D or H' and Σ_G regardless of the individual values of load and speed, and regardless of the individual values of viscosity which occur due to moderate temperature differences resulting from internal heat generation in the bearings. However, as indicated by the data presented in Figures 15, 16, and 17, there is apparently some effect which is not accounted for by the parameters Σ_D and Σ_G. These three figures show that for three oils of considerably different viscosity grades, the slope of the curves of H versus Σ_D and H' versus Σ_G increase progressively with an increase in the viscosity grade of the oil. For the most viscous oil, the Nye 860-2, the measured film thickness data are in excellent agreement with the theoretical equations of Grubin and Dowson for flooded isothermal conditions. For the two other oils, the BBRC 36233 and

Apiezon A with additives, the measured EHD film thicknesses are less than predicted by the theoretical equations. While this disagreement could be attributed to thermal effects caused by viscous heating in the conjunction inlets, as noted in the results of the optical EHD film thickness measurements from Task I, this is not believed likely. If viscous heating was responsible, then the effects would be expected to be present in all three cases. Moreover, these effects should be greater for the case of the most viscous oil but, as noted above, an opposite trend is observed. It is believed that a more plausible explanation is that oil starvation is responsible for the lack of agreement with the theoretical equations. This starvation effect could be due to the balls pushing the oil out of the running track, but what is probably more likely is that the retainer is actually wiping some of the oil from the balls. Apparently, this wiping action is more severe for the least viscous oil.

Also from the results obtained in Task II, it is concluded that there is no significant effect of additives or ball-race composite surface roughness on the development of EHD films within the bearings.

Finally, by comparing Figures 16, 20, 21, and 22, it is also concluded that the EHD film thicknesses which develop within the bearing are not significantly affected by the thickness of the initial oil film coating applied to the bearings, at least for the range of initial film thickness coatings investigated in this study. The thinnest initial oil film coating used was approximately 0.1 μm (4 μin.). For initial oil film coatings thinner than this, even more severe starvation effects may be expected.

Task III. From the post-test examinations of the bearings from the two long-duration tests where the bearings failed, it is concluded that the failure was due to a lubrication problem at the interfaces between the retainer and the other bearing components and not due to inadequate EHD film thicknesses at the ball-race contacts. It is further concluded that this problem is associated with lubricant feed from the retainer to the balls and to the interfaces where the retainer rubs on the lands of the bearing. Considering the fabrication technique used for the cotton-phenolic retainer material, it is evident that it is possible for lubricant feed to occur from the retainer to the balls. However, it does not appear possible for lubricant feed to occur from the phenolic to the lands of the bearing. This is because the layers of cotton material in the phenolic are parallel to the bearing lands, and lubricant feed cannot occur in a direction perpendicular to these layers. The bearings used in the present study have outer-land-riding cages. Thus the rubbing which occurs between the retainer and the outer lands of the bearing cause a torque on the retainer which opposes the driving torque. Since there cannot be lubricant feed from the retainer to the retainer-bearing land interface, the lubrication of that interface must largely depend upon the initial oil coating on the two surfaces. If this coating is depleted, then it is possible for excessive resisting torques to develop thus requiring a greater force between the balls and the retainer. This can accelerate the retainer wear at the ball pockets and can cause a glazing of the retainer at the ball pockets thus impeding lubricant feed at the ball-retainer interfaces. It is believed that this retainer problem can be alleviated by the use of a ball-piloted retainer. In that case, all locations where the retainer contacts the other bearing components are capable of receiving lubricant feed from the retainer.

From the measurements of the EHD film thicknesses in the bearing using the race displacement technique, the Λ_m ratio for the tests where Apiezon A with additives was employed was as low as 0.71. Yet examination of the bearing races and balls indicated that little, if any, rubbing wear occurred. It is thus concluded that lubrication was very nearly in the full EHD regime for these tests. Consequently, it has not been possible to determine the effect of Λ_m on the bearing-lubricant system life. However, it has been established from these tests that for periods of about 4000 hours, satisfactory operation from an EHD film standpoint can be attained at Λ_m values of the order of unity or slightly less.

2. Recommendations

In view of the apparent starvation effects observed in the Task II and Task III work, as exemplified by the measured EHD film thicknesses in the bearings being less than the theoretically predicted values, several further studies are recommended. First, it is believed important to study and define the effectiveness of oil feed from retainers. It is recommended that several different retainer materials be investigated, including the contemporary phenolic material, and also several more advanced materials which might provide improved lubricant feed characteristics.

It is also recommended that the effect of retainer/bearing processing variations be studied further. To define more completely the effects of initial oil film thickness on the development of adequate EHD film thicknesses within the bearing, it is recommended that several processing conditions be used that will result in initial oil film thickness coatings less than the thinnest initial coating of 0.1 μm (4 μin.) employed in this study. The objective would be to define the thickness of the coating below which severe oil starvation would occur.

Because the Task II and Task III tests involved only moderate changes in bearing temperature, it is also recommended that the effect of temperature variation on the development and maintenance of adequate EHD films be studied more completely. This can be done by cycling the environmental temperature of the bearing test chambers to produce the same temperature environment as is experienced by DMA bearings in actual space service.

Finally, it is recommended that further long-term testing be done to define the influence of the Λ_m ratio on bearing-lubricant performance and life expectancy. This should be done using rougher bearing races than were employed in the present study to produce Λ_m values low enough to place operation in the boundary lubrication regime. The bearing retainer design should be changed to ball-piloted retainers so that bearing seizure due to the retainers can be avoided. It is also recommended that the effects of antiwear additive concentration be included in these long-term studies. This is because when lubrication is in the boundary lubrication regime, with asperity interactions occurring, the antiwear additive plays an important role in determining the wear rate due to rubbing of the bearing components. The potential of the Λ_m level and additive concentration as accelerating factors for bearing-lubricant life-expectancy tests can thus be established.

APPENDIX A

DEVELOPMENT OF FILM THICKNESS — BEARING RACE DISPLACEMENT EQUATIONS USED IN COMPUTER PROGRAMS

1. General

Before the race displacement technique can be used to make measurements of the oil film thickness in an angular contact bearing, a relationship between the EHD films which develop in the ball-race conjunctions and the axial displacement of the movable bearing race must be determined. For this purpose, an analogy can be drawn between the axial race displacement due to a slight change in ball diameter, and that due to the development of EHD films in the ball-race conjunctions.

Consider now the sketch in Figure 31, which is a cross section taken through the center of a ball in an angular contact bearing. The upper race in the sketch is considered to be the rotating inner race, and the lower one is the outer race which is elastically restrained in the axial direction. Let the initial ball size and outer race position be represented by the solid lines. Consider now that the ball is replaced by one of a slightly larger size, indicated by the broken lines, with no other changes in the bearing being made. The inner race is held stationary axially, thus the outer race must move to the new position, shown by the broken lines, to accommodate the larger ball. The axial distance that the outer race moves is ΔS, which is also the distance moved by the center of the outer race curvature, i.e., from C_i to C_i'. The initial contact angle, β_o, will decrease slightly to β_o', while the initial contact points on the inner and outer races will change from A and B to A' and B'. If the increase in ball diameter is Δd then it may be shown(9) that the axial displacement ΔS is related to the change in ball diameter by

$$\Delta S = B_o d_o (\sin \beta_o - \beta_o') + \Delta d \sin \beta_o' \qquad (12)$$

where ΔS = axial displacement of outer race

B_o = total curvature referred to original ball diameter

$= \dfrac{r_o}{d_o} + \dfrac{r_i}{d_o} - 1$

r_o = radius of curvature of outer race (transverse to raceway)

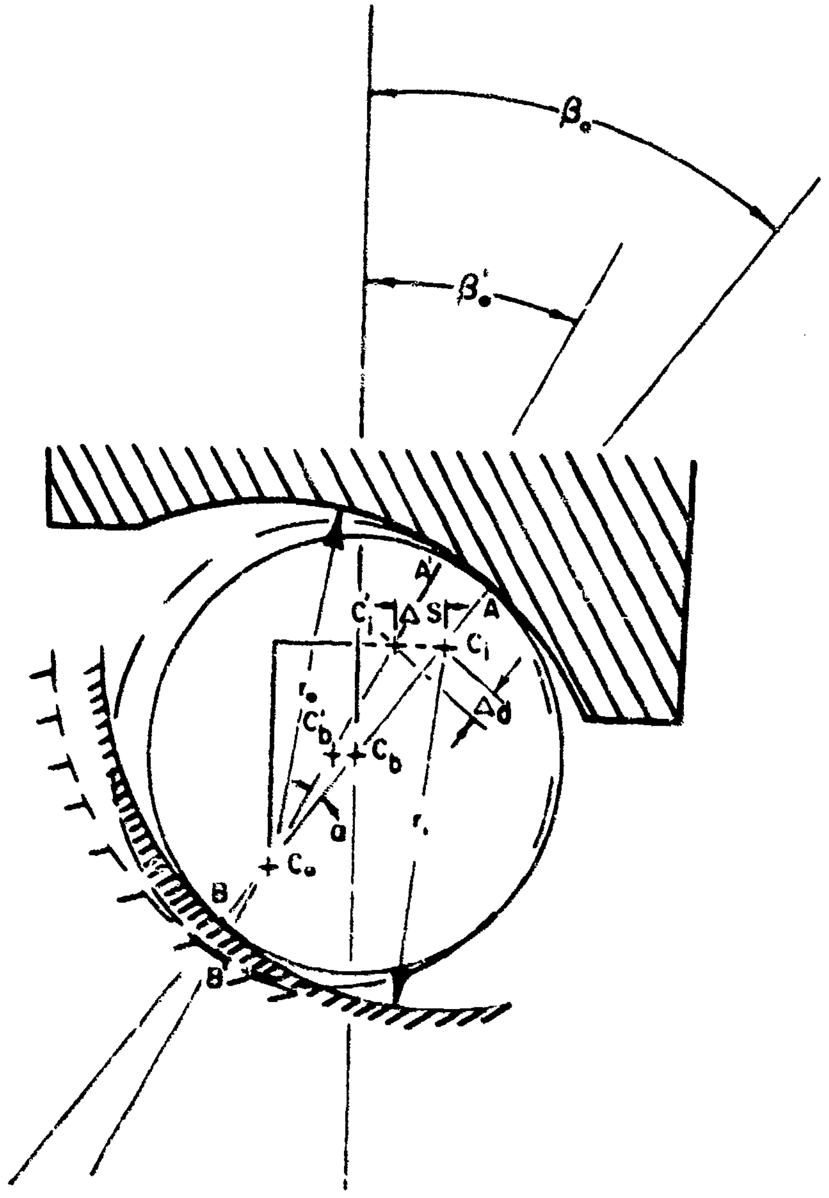

β_o
β'_o
A'
C'_i
ΔS
A
C_i
Δd
r_o
C'_b
C_b
a
r_i
C_o
B
B'

Figure 31. Schematic Drawing Showing Axially Displaced Bearing Race

r_i = radius of curvature of inner race (transverse to raceway)

d_o = original ball diameter

β_o = original contact angle

β_o' = contact angle after race displacement

Δd = increase in ball diameter

It may also be shown that the "new" contact angle is related to the initial contact angle by

$$\cos \beta_o' = \frac{B_o d_o \cos \beta_o}{B_o d_o - \Delta d} \tag{13}$$

2. System of Equations Relating Central-Region EHD Film Thickness to Bearing Displacement

Now imagine that instead of the outer race being displaced axially by increasing the ball diameter, it is displaced by the development of EHD films at the inner and outer ball-race conjunctions. If it is assumed that the axial displacement is due to the central-region EHD film thickness, then we may write

$$\Delta d = h_i' + h_o' \tag{14}$$

where h_i' = central-region EHD film thickness at ball-inner race contacts

h_o' = central-region EHD film thickness at ball-outer race contacts

Substituting Eqs. (13) and (14) into Eq. (12), then

$$\Delta S = B_o d_o \left\{ \sin \beta_o - \sin \left[\arc\cos \left(\frac{B_o d_o \cos \beta_o}{B_o d_o - (h_i' + h_o')} \right) \right] \right\}$$

$$+ (h_i' + h_o') \sin \left[\arc\cos \left(\frac{B_o d_o \cos \beta_o}{B_o d_o - (h_i' + h_o')} \right) \right] \tag{15}$$

represents the axial displacement for one bearing.

If the axial displacement ΔS is a known quantity obtained by measurement, and the bearing geometry is defined, then Eq. (15) contains two unknowns, h_i' and h_o'. Hence an equation is needed relating h_i' to h_o'.

Considering for the present only the contacts at the inner race of the bearing and applying Eq. (8) and the definitions for G and U_t

$$H_i' = \frac{h_i'}{R_i} = 1.18 \; \frac{(\alpha_o \overset{*}{E})^{0.73} \left(\dfrac{\mu_o V_t}{\overset{*}{E} R_i}\right)^{0.73}}{W_{ei}^{0.09}} \tag{16}$$

Now for a given bearing operating at a given speed, load, and temperature, the variables $\overset{*}{E}$, α_o, μ_o, and V_t will be constant. For that situation Eq. (16) may be written

$$\frac{h_i'}{R_i} = \frac{C}{W_{ei}^{0.09} \, R_i^{0.73}}$$

or $$h_i' = C \, \frac{R_i^{0.27}}{W_{ei}^{0.09}} \tag{17}$$

where $C = 1.18 \, (\alpha_o \overset{*}{E})^{0.73} \left(\dfrac{\mu_o V_t}{\overset{*}{E}}\right)^{0.73}$

Applying Eq. (10) to the inner race contacts

$$W_{ei} = \frac{w_{ei}}{\overset{*}{E} R_i} = \frac{3P}{4a_i \, \overset{*}{E} R_i} \tag{18}$$

where all symbols are as previously defined, and the subscript "i" is used to denote the inner race. For the bearings used in the present program the semiwidth of the major axis of the contact ellipse at the ball-inner race contacts is given by

$$a_i = 0.16467\, P^{1/3} \tag{19}$$

where a_i = mm, P = Newtons. Substituting Eq. (19) into Eq. (18)

$$W_{ei} = 4.55456 \, \frac{P^{2/3}}{\overset{*}{E} R_i}$$

or, at constant load

$$W_{ei} = C_1 \, \frac{4.55456}{R_i} \tag{20}$$

where $C_1 = P^{2/3}/\overset{*}{E}$. Now substituting Eq. (20) into Eq. (17)

$$h_i' = C \, \frac{R_i^{0.27}}{\left(C_1 \, \dfrac{4.55456}{R_i}\right)^{0.09}}$$

or $$h_i' = 0.87245\, C_2\, R_i^{0.36} \tag{21}$$

where $C_2 = C/C_1^{0.09}$

For the bearings used in the present study, R_i = 7.03148 mm (0.27683 in.). With this value substituted into Eq. (21)

$$h_i' = 1.76066\, C_2 \tag{22}$$

Now the same exercise given by Eqs. (16) through (22) may be repeated for the ball-outer race contacts. The assumption is made that within a given bearing the temperature of the oil at the conjunction inlets of the ball-inner race contacts is the same as that at the ball-outer race contacts; then μ_0 and α_0 will be the same at all contacts within the bearing.

For the bearings used in the present study, the semiwidth of the major axis of the contact ellipse at the ball-outer race contacts is given by

$$a_o = 0.16178\, P^{1/3} \tag{23}$$

where a_o = mm, P = Newtons. The equivalent radius at the ball-outer race contacts is R_o = 8.84352 mm (0.34817 in.). Following the same procedure as given by Eqs. (16) through (22) for the outer race we obtain

$$h'_o = 1.90912\,C_2 \tag{24}$$

Dividing Eq. (24) by Eq. (22) and rearranging

$$h'_o = 1.08432\,h'_i \tag{25}$$

In other words, due to the better conformity at the ball-outer race contacts, the central-region EHD film thickness is about 8 percent thicker there than at the ball-inner race contacts.

Substituting Eq. (25) into Eq. (15)

$$\Delta S = B_o d_o \left[\sin\beta_o - \sin\left[\arc\cos\left(\frac{B_o d_o \cos\beta_o}{B_o d_o - 2.08432\,h'_i}\right)\right]\right] + 2.08432\,h'_i \sin\left[\arc\cos\left(\frac{B_o d_o \cos\beta_o}{B_o d_o - 2.08432\,h'_i}\right)\right] \tag{26}$$

The axial displacement ΔS given by Eq. (26) is for a single bearing. Since there are two bearings in each of the test rigs used in Task II and Task III, the total axial displacement, ΔLy, measured by the LVDT system is the sum of the displacements of the forward and aft bearings. That is

$$\Delta Ly = \Delta S_{aft} + \Delta S_{fwd} \tag{27}$$

where ΔS_{aft} = contribution of aft bearing to total axial displacement

ΔS_{fwd} = contribution of forward bearing to total axial displacement

Now applying Eq. (26) to the ball-inner race contacts of both bearings and substituting into Eq. (27)

$$\Delta Ly = B_o d_o \left[\sin \beta_o - \sin \left[\arc\cos\left(\frac{B_o d_o \cos \beta_o}{B_o d_o - 2.08432\, h_{i\,(aft)}'}\right)\right]\right]$$

$$+ 2.08432\, h_{i\,(aft)}' \sin \left[\arc\cos\left(\frac{B_o d_o \cos \beta_o}{B_o d_o - 2.08432\, h_{i\,(aft)}'}\right)\right]$$

$$+ B_o d_o \left[\sin \beta_o - \sin \left[\arc\cos\left(\frac{B_o d_o \cos \beta_o}{B_o d_o - 2.08432\, h_{i\,(fwd)}'}\right)\right]\right]$$

$$+ 2.08432\, h_{i\,(fwd)}' \sin \left[\arc\cos\left(\frac{B_o d_o \cos \beta_o}{B_o d_o - 2.08432\, h_{i\,(fwd)}'}\right)\right] \quad (28)$$

In most cases the two bearings in a given test rig do not operate at the same temperature, and bearing temperature affects lubricant viscosity and pressure viscosity coefficient hence EHD film thickness. Thus in general $h_{i\,(aft)}' \neq h_{i\,(fwd)}'$ and some analytical scheme must be employed to relate $h_{i\,(aft)}'$ to $h_{i\,(fwd)}'$.

Returning to Eq. (16), for the two given bearings operating at constant speed and load, the variables W_{ei} and V_t are constant. Since $\overset{*}{E}$ and R_i are also constant, Eq. (16) may be written

$$h_i' = C_3\, (\alpha_o \mu_o)^{0.73} \quad (29)$$

where $C_3 = 1.18 \dfrac{R_i^{0.27}\, V_t^{0.73}}{W_{ei}^{0.09}}$

Applying Eq. (29) to the ball-inner race contacts of the forward and aft bearings

$$h_{i\,(aft)}' = C_3\, (\alpha_o \mu_o)_{aft}^{0.73} \quad (30)$$

$$h_{i\,(fwd)}' = C_3\, (\alpha_o \mu_o)_{fwd}^{0.73} \quad (31)$$

Dividing Eq. (31) by Eq. (30) and rearranging

$$h_i'(\text{fwd}) = \psi h_i'(\text{aft}) \tag{32}$$

$$\text{where } \psi = \left[\frac{(\alpha_o\mu_o)\text{fwd}}{(\alpha_o\mu_o)\text{aft}}\right]^{0.73}$$

Now Eq. (32) may be substituted into Eq. (28) to yield

$$\begin{aligned}\Delta Ly = B_od_o\Bigg\{&\left[\sin\beta_o - \sin\left[\arc\cos\left(\frac{B_od_o\cos\beta_o}{B_od_o - 2.08432\,h_i'(\text{aft})}\right)\right]\right]\\ &+\left[\sin\beta_o - \sin\left[\arc\cos\left(\frac{B_od_o\cos\beta_o}{B_od_o - 2.08432\,\psi h_i'(\text{aft})}\right)\right]\right]\Bigg\}\\ +\,2.08432\Bigg\{&h_i'(\text{aft})\sin\left[\arc\cos\left(\frac{B_od_o\cos\beta_o}{B_od_o - 2.08432\,h_i'(\text{aft})}\right)\right]\\ &+\psi h_i'(\text{aft})\sin\left[\arc\cos\left(\frac{B_od_o\cos\beta_o}{B_od_o - 2.08432\,\psi h_i'(\text{aft})}\right)\right]\Bigg\}\end{aligned} \tag{33}$$

For each set of operating conditions, the value of the temperature correction factor ψ can be determined using the measured bearing temperatures to evaluate α_o and μ_o for the forward and aft bearings. Then with the measured value of ΔLy, and the known geometric quantities B_o, d_o, and β_o for the bearings, Eq. (33) can be solved iteratively for $h_i'(\text{aft})$, the EHD film thickness at the ball-inner race contacts of the aft bearing. Once $h_i'(\text{aft})$ has been calculated, then $h_i'(\text{fwd})$, $h_o'(\text{aft})$, and $h_o'(\text{fwd})$ can be calculated using Eqs. (25) and (32)

3. System of Equations Relating Minimum EHD Film Thickness to Bearing Displacement

The development of the following system of equations relating minimum EHD film thickness to bearing displacement follows a line of reasoning identical to that given above for relating central-region EHD film thickness to bearing displacement. Consequently, for the sake of brevity, the development of the system equations will not be presented here in great detail. The development begins by assuming that the measured axial displacement is due to the minimum EHD film thickness, then similar to Eq. (14) we write

$$\Delta d = h_i + h_o \tag{34}$$

where h_i = minimum EHD film thickness at ball-inner race contacts

h_o = minimum EHD film thickness at ball-outer race contacts

Then an equation identical to Eq. (15) results except that h_i' and h_o' are replaced by h_i and h_o respectively.

Instead of Eq. (8) we use Eq. (9) to obtain

$$H_i = \frac{h_i}{R_i} = 1.63 \, \frac{(\alpha_o \overset{*}{E})^{0.54} \left(\dfrac{\mu_o V_t}{\overset{*}{E} R_i} \right)^{0.70}}{W_{ei}^{0.13}} \tag{35}$$

From this point an identical line of reasoning yields

$$h_o = 1.10109 \, h_i \tag{36}$$

which may be compared with Eq. (25). That is, the minimum EHD film thickness at the ball-outer race contacts is about 10 percent thicker than at the ball-inner race contacts.

Continuing the development it is found that

$$h_i(\text{fwd}) = \zeta \, h_i(\text{aft}) \tag{37}$$

$$\text{where } \zeta = \left[\left(\frac{\alpha_o(\text{fwd})}{\alpha_o(\text{aft})} \right)^{0.54} \left(\frac{\mu_o(\text{fwd})}{\mu_o(\text{aft})} \right)^{0.70} \right]$$

The key equation which follows is

$$\Delta Ly = B_o d_o \Bigg\{ \left[\sin \beta_o - \sin \left[\arccos \left(\frac{B_o d_o \cos \beta_o}{B_o d_o - 2.10109 \, h_{i(\text{aft})}} \right) \right] \right] + \left[\sin \beta_o - \sin \left[\arccos \left(\frac{B_o d_o \cos \beta_o}{B_o d_o - 2.10109 \, \zeta \, h_{i(\text{aft})}} \right) \right] \right] \Bigg\}$$

$$+ 2.10109 \left\{ h_i(\text{aft}) \sin \left[\arccos \left(\frac{B_o d_o \cos \beta_o}{B_o d_o - 2.10109\, h_i(\text{aft})} \right) \right] + \zeta\, h_i(\text{aft}) \sin \left[\arccos \left(\frac{B_o d_o \cos \beta_o}{B_o d_o - 2.10109\, \zeta\, h_i(\text{aft})} \right) \right] \right\} \quad (38)$$

As described above, for each set of operating conditions, the value of the temperature correction factor ζ can be determined, and with the measured ΔLy, Eq. (38) may be solved iteratively for $h_i(\text{aft})$. Then $h_i(\text{fwd})$, $h_o(\text{aft})$, and $h_o(\text{fwd})$ can be calculated using Eqs. (36) and (37).

APPENDIX B

LISTING FOR TASK II DATA REDUCTION PROGRAM

```
                 PROGRAM DROFT (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
            C                      *  DATA REDUCTION FOR OIL FILM   *
            C                      *  THICKNESS IN DMA BEARINGS,    *
            C                      *  PROGRAMMED BY HERB CARPER,    *
            C                      *  JOHN TYLER,AND MARY CARTER    *
            C                      * * * * * * * * * * * * * * * * *
            C
000003           DIMENSION AN(4),DELTLV(4),HCAI(4),HMAI(4),HCAO(4),HMAO(4),HCFI(4),
                *          HMFI(4),HCFO(4),HMFO(4),HXCAI(4),HXMAI(4),HXCAO(4),
                *          HXMAO(4),HXCFI(4),HXMFI(4),HXCFO(4),HXMFO(4),HXCAIS(4),
                *          HXMAIS(4),HXCFIS(4),HXMFIS(4),HXCAOS(4),HXMAOS(4),
                *          HXCFOS(4),HXMFOS(4),HCAIS(4),HMAIS(4),HCAOS(4),HMAOS(4),
                *          HCFIS(4),HMFIS(4),HCFOS(4),HMFOS(4),TORQUE(4),TORQSI(4),
                *          NOIL(8)
000003           COMMON VIS,XK,BETA,ALPHAO,PHI,OMEGA,P,GAM,G,REQO,REQI,DHXAI,DHXFI,
                *       DHXAO,DHXFO,RATIO,RBALL,RRACE,S,ESTAR,DELTL,RATIOA,RATIOV
000003           EXTERNAL DELTAC,DELTAM
000003      1000 FORMAT ( 8A10 )
000003      1016 FORMAT ( 2A5, I5 )
000003         1 CONTINUE
000003           READ (5,1000) NOIL
000011           IF (EOF,5) 160,2
000014         2 READ (5,1016) NBEAR,NTHCK,NTEST
            C
            C  BEARING GEOMETRY AND MATERIAL (NOTE UNITS ARE CONVERTED TO SI SYSTEM)
            C
000026           RBALL=0.1125*2.54E-2
000027           RRACE=2.179 *2.54E-2
000031           S=RBALL/RRACE
000032           ESTAR=31.E6*6.895E3
000034           PHI=26.*3.14159/180.
000035           REQI=0.27693*2.54E-2
000037           REQO=0.34817*2.54E-2
000041           READ (5,1001) XLOAD
000046      1001 FORMAT (F3.0)
000046           XLOADS=XLOAD*4.448
000050           P=XLOAD/10.*SIN(PHI)
000054           AI=0.01066*P**(1./3.)
000062           AO=0.01047*P**(1./3.)
000070           P=P*4.448
000072           AI=AI*2.54E-2
000074           AO=AO*2.54E-2
000076           READ (5,1002) A,B,GAM,G,XK,BETA
000115      1002 FORMAT(3F10.5,F10.6,E10.3,F10.5)
000115           NPAGE=1
000116        10 CONTINUE
000116           WRITE (6,1003) NTEST,NOIL,NBEAR,NTHCK,XLOADS,XLOAD
000136           READ (5,1004) BASEN,TEMPA,TEMPF,NSPEED,PRESS
000154      1004 FORMAT (3F3.0,I3,E10.3)
000154           PRESSI=PRESS*133.3
000156           OMEGA=BASEN*2.*3.14159/60.
000160           TEMPAS=(TEMPA-32.)*5./9.
000163           TEMPFS=(TEMPF-32.)*5./9.
            C
            C  BASE CALCULATIONS FOR AFT BEARING
            C
000166           CALL FLPROP (TEMPAS,A,B,GAM,G,XK,BETA,ALPHAO,VIS)
```

```
            C
            C  INNER CONTACTS
            C
000176            CALL FILM (REQI,AI,BHCAI,BHMAI)
            C
            C  OUTER CONTACTS
            C
000201            CALL FILM (REQO,AO,BHCAO,BHMAO)
            C
            C  FILM THICKNESS CALCULATIONS FOR AFT BEARING
            C
000204            READ (5,1005) ((XN(I),DELTLV(I),TORQUE(I)),I=1,NSPEED)
000223       1005 FORMAT ( 12F5.1 )
000223            DO 20 I=1,NSPEED
            C
            C  INNER CONTACTS
            C
000225            OMEGA=XN(I)*2.*3.14159/60.
000227            CALL FILM (REQI,AI,HCAI(I),HMAI(I))
            C
            C  OUTER CONTACTS
            C
000232         20 CALL FILM (REQO,AO,HCAO(I),HMAO(I))
000241            ALMUA=ALPHAO*VIS
000242            ALFAFT=ALPHAO
000243            VISAFT=VIS
            C
            C  PHASE CALCULATIONS FOR FORWARD BEARING
            C
000244            OMEGA=PHASEN*2.*3.14159/60.
000247            CALL FLPROP (TEMPFS,A,B,GAM,G,XK,BETA,ALPHAO,VIS)
            C
            C  INNER CONTACTS
            C
000257            CALL FILM (REQI,AI,BHCFI,BHMFI)
            C
            C  OUTER CONTACTS
            C
000262            CALL FILM (REQO,AO,BHCFO,BHMFO)
            C
            C  FILM THICKNESS CALCULATIONS FOR FORWARD BEARING
            C
000265            DO 40 I=1,NSPEED
            C
            C  INNER CONTACTS
            C
000267            OMEGA=XN(I)*2.*3.14159/60.
000271            CALL FILM (REQI,AI,HCFI(I),HMFI(I))
            C
            C  OUTER CONTACTS
            C
000274         40 CALL FILM (REQO,AO,HCFO(I),HMFO(I))
000303            ALMUF=ALPHAO*VIS
000304            RATIOM=ALMUF/ALMUA
000306            RATIOA=ALPHAO/ALFAFT
000307            RATIOV=VIS/VISAFT
            C
            C  EXPERIMENTAL FILM THICKNESSES CALCULATED FROM MEASURED BEARING
            C  DISPLACEMENT
            C
            C  FIRST SOLVE FOR INCREMENT IN FILM THICKNESS AT INNER CONTACTS OF AFT
            C  BEARING (IN MICROINCHES)
000311            NX=30
000312            DX=10.
000314            EPS=0.01
000315            DO 50 I=1,NSPEED
000317            MX=0.0
000320            IER=0
000320            DELTA=DELTLV(I)
000322            CALL BISECT (MX,NX,DX,EPS,IER,DELTAC)
000326            IF (IER.EQ.0) GO TO 45
[illegible]    44 WRITE (6,4444)
[illegible]  4444 FORMAT (//* ERROR- NO CHANGE OF SIGN FOUND IN SEARCH RANGE*)
000334            STOP
000335         45 DHXCA=XMX
000336            MX=0.0
000337            IER=0
000340            DELTA=DELTLV(I)
000342            CALL BISECT (MX,NX,DX,EPS,IER,DELTAM)
000344            IF (IER.NE.0) GO TO 44
000347            DHXMA=XMX
            C
            C  SOLVE FOR INCREMENT IN FILM THICKNESS FOR INNER CONTACTS OF FORWARD
            C  BEARING BY USING CORRECTION FOR BEARING TEMPERATURE DIFFERENCE
            C
000350            DHXCFI=RATIO**0.7*DHXCAI
000356            DHXMFI=RATIO**0.5*RATIOV**0.7*DHXMAI
            C
            C  SOLVE FOR INCREMENT IN FILM THICKNESS FOR OUTER CONTACTS OF BOTH
            C  BEARINGS USING CORRECTION FOR GEOMETRY EFFECTS
            C
000366            DHXCAO=1.0812*DHXCAI
000366            DHXCFO=1.0812*DHXCFI
000370            DHXMAO=1.1010*DHXMAI
000372            DHXMFO=1.1010*DHXMFI
            C
            C  CONVERT FILM THICKNESS INCREMENTS FROM MICROINCHES TO METERS
            C
000374            C1=2.54E-2/1.0E6
000375            DHXCAI=DHXCAI*C1
000376            DHXCFI=DHXCFI*C1
000400            DHXCAO=DHXCAO*C1
000401            DHXCFO=DHXCFO*C1
000402            DHXMAI=DHXMAI*C1
000403            DHXMFI=DHXMFI*C1
000404            DHXMAO=DHXMAO*C1
000405            DHXMFO=DHXMFO*C1
            C
            C  NONDIMENSIONALIZE FILM THICKNESS INCREMENTS
            C
000406            DHXCAI=DHXCAI/REQI
[illegible]       DHXCFI=DHXCFI/REQI
000411            DHXCAO=DHXCAO/REQO
000412            DHXCFO=DHXCFO/REQO
000413            DHXMAI=DHXMAI/REQI
000415            DHXMFI=DHXMFI/REQI
```

```
000416          OMEGAO=OMEGAO/REGO
000417          OMEGFO=OMEGFO/REGO
         C
         C  FILM THICKNESSES IN AFT BEARING (INCREMENT PLUS BASE)
         C
000420          HCAI(I)=DHHCAI+HHCAI
000421          HWAI(I)=DHWAI+HHWAI
000426          HCAO(I)=DHCAO+HHCAO
000433          HWAO(I)=DHWAO+HHWAO
         C
         C  FILM THICKNESSES IN FORWARD BEARING (INCREMENT PLUS BASE)
         C
000434          HCFI(I)=DHHCFI+HHCFI
000435          HWFI(I)=DHWFI+HHWFI
000440          HCFO(I)=DHCFO+HHCFO
000442       50 HWFO(I)=DHWFO+HHWFO
         C
         C  CONVERT FILM THICKNESSES FROM DIMENSIONLESS TO MICROMETERS
         C
000447          CI=RECI*1.E6
000450          CO=RFCO*1.E6
000451          HHCAIS=HHCAI*CI
000454          HHWAIS=HHWAI*CI
000455          HHCFIS=HHCFI*CI
000456          HHWFIS=HHWFI*CI
000460          HHCAOS=HHCAO*CO
000462          HHWAOS=HHWAO*CO
000463          HHCFOS=HHCFO*CO
000465          HHWFOS=HHWFO*CO
000467          DO 60 I=1,NSPEED
000470          HHCAIS(I)=HHCAI(I)*CI
000472          HHWAIS(I)=HHWAI(I)*CI
000474          HHCFIS(I)=HHCFI(I)*CI
000475          HHWFIS(I)=HHWFI(I)*CI
000477          HHCAOS(I)=HHCAO(I)*CO
000501          HHWAOS(I)=HHWAO(I)*CO
000502          HHCFOS(I)=HHCFO(I)*CO
000504          HHWFOS(I)=HHWFO(I)*CO
000505          HCAIS(I)=HCAI(I)*CI
000507          HWAIS(I)=HWAI(I)*CI
000511          HCFIS(I)=HCFI(I)*CI
000512          HWFIS(I)=HWFI(I)*CI
000514          HCAOS(I)=HCAO(I)*CO
000516          HWAOS(I)=HWAO(I)*CO
000517          HCFOS(I)=HCFO(I)*CO
000521       60 HWFOS(I)=HWFO(I)*CO
         C
         C  CONVERT TORQUE,LOAD,AND TEMPERATURE TO SI UNITS
         C
000525          DO 70 I=1,NSPEED
000526       70 TORQSI(I)=TORQUE(I)*7.0612E-3
000531          ALOADS=4.448*ALOAD
         C
         C  CONVERT FILM THICKNESSES FROM DIMENSIONLESS TO MICROINCHES
         C
000534          RIECI=CI*39.37
000536          ROECO=CO*39.37
000540          H=CAI=HHCAI*RI
```

```
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      DO 80 I=1,NSPEED
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible]
   80 [illegible]
      WRITE (6,1006) TEMPAS,TEMPA,TEMPFS,TEMPF,PRESI,PRESS
      GO TO (90,100,110) NPAGE
   90 WRITE (6,1007) BASEN
      NPAGE=2
      GO TO 120
  100 WRITE (6,1008) BASEN
      NPAGE=3
 1003 FORMAT (1H1////' TEST NO. ',I3/' OIL = ',A10/
     *        ' BEARING ROUGHNESS = ',A5/' INITIAL FILM THICKNESS = ',A5/
     *        ' LOAD(N)               = ',F5.0,9X,'LOAD(LB)               = ',F5.0)
 1006 FORMAT(' AFT TEMP(C)           = ',F5.1,9X,'AFT TEMP(F)            = ',F5.1/
     *        ' FWD TEMP(C)           = ',F5.1,9X,'FWD TEMP(F)            = ',F5.1/
     *        ' PRESSURE(PASCAL) =',E10.3,5X,'PRESSURE(TORR)       =',E10.3)
 1007 FORMAT (//' PRE PUMP DOWN RESULTS'//8X,'BASE SPEED(RPM) = ',F5.1)
 1008 FORMAT (//' INITIAL AFTER PUMP DOWN RESULTS'//5X,'BASE SPEED(RPM)
     *= ',F5.1)
 1009 FORMAT (//' 20 HOURS AFTER PUMP DOWN'//8X,'BASE SPEED(RPM) = ',
     *F5.1)
 1010 FORMAT (///5X,'FILM THICKNESS(MICRONS)',A10///31X,'AFT BEARING',45X,
     *                       'FORWARD BEARING'//3X,2(15X,'OUTER CONTACTS',15X,
     *                       'INNER CONTACTS')/ /15X,'SMCAO',9X,'SMMAO',10X,
     *                       'SMCAI',9X,'SMMAI',10X,'SMCFO',9X,'SMMFO',10X,
     *                       'SMCFI',9X,'SMMFI' )
 1011 FORMAT (5X,4(F15.3,F14.3) / 12X,'TORQUE' )
 1012 FORMAT (5X,4(F15.2,F14.2) / 12X,'TORQUE' )
 1013 FORMAT (1X,'SPEED(RPM)',4(' (CONC',3X,'ECCENC',3X,'THINC',3X,
     *                 'SMIN    '),2X,A1 )
 1014 FORMAT (2X,F6.2,4(1X,3F7.3),4X,F7.3)
 1015 FORMAT (2X,F6.2,4(1X,4F7.2),4X,F7.1)
      GO TO 120
  110 WRITE (6,1009) BASEN
      NPAGE=1
  120 WRITE([illegible])
      WRITE (6,1010) NTITLE
      WRITE (6,1011)  BMCAOS,BMMAOS,BMCAIS,BMMAIS,BMCFOS,BMMFOS,BMCFIS,
     *                BMMFIS
      WRITLINE (NOW)
      WRITE (6,1012)  WTITLE
      DO 140 I=1,NSHIFO
      WRITE (6,1014) TO(I),MCAOS(I),MXCAOS(I),MMAOS(I),MXMAOS(I),
     *               MCAIS(I),MXCAIS(I),MMAIS(I),MXMAIS(I),MCFOS(I),
     *               MXCFOS(I),MMFOS(I),MXMFOS(I),MCFIS(I),MXCFIS(I),
     *               MMFIS(I),MXMFIS(I),TORQS(I)
  140 CONTINUE
      WTITLE(19)=NOMCAT(5)
      WRITE (6,1010) WTITLE
      WRITE (6,1014) BMCAO,BMMAO,BMCAI,BMMAI,BMCFO,BMMFO,BMCFI,BMMFI
      WTITLE(19)=IO(4)
      WRITE (6,1012) WTITLE
      DO 150 I=1,NSHID
      WRITE (6,1015) TO(I),MCAO(I),MXCAO(I),MMAO(I),MXMAO(I),MCAI(I),
     *               MXCAI(I),MMAI(I),MXMAI(I),MCFO(I),MXCFO(I),MMFO(I),
     *               MXMFO(I),MCFI(I),MXCFI(I),MMFI(I),MXMFI(I),
     *               TORQUE(I)
  150 CONTINUE
      IF (NPAGE.LT.N) GO TO 10
      GO TO 1
  160 CONTINUE
      END
```

```
               SUBROUTINE  FLPROP (T,A,B,GAM,G,XK,BETA,ALPHAO,E)
000014         Y=ALOG10(T+273.)
000023         X=A-B*Y
000025         E=10.**(10.**X)-0.6
000035         E=E*(GAM-G*(T-15.6))*0.001
000042         ALPHAO=XK/T**BETA
000047         RETURN
000050         END
```

```
                 SUBROUTINE FILM (REQ,A,HC,HM)
000007           COMMON VIS,XK,BETA,ALPHAO,PHI,OMEGA,P,GAM,G,REQO,REQI,DHXAI,DHXFI,
                *       DHXAO,DHXFO,RATIO,RBALL,RRACE,S,ESTAR,DELTL,RATIOA,RATIOV
            C
            C   CALCULATE DIMENSIONLESS CENTRAL-REGION FILM THICKNESS
            C
000007           X1=(1.+2.*S*COS(PHI))/(2.*S*(1.+S*COS(PHI)))
000022           X2=(VIS*2.*RBALL*X1*OMEGA)/(ESTAR*REQ)
000033           X3=X2**0.73
000037           X4=(ALPHAO*ESTAR)
000041           X5=X4**0.73
000044           X6=3.+P/(4.*A*ESTAR*REQ)
000050           X7=X6**0.09
000054           HC=1.19*X5*X3/X7
            C
            C   CALCULATE DIMENSIONLESS MINIMUM FILM THICKNESS
            C
000057           X8=X2**0.70
000063           X9=X4**0.54
000067           X10=X6**0.13
000073           HM=1.63*X9*X8/X10
000077           RETURN
000077           END
```

```
                FUNCTION DELTAC (HX)
000003          COMMON VIS,XK,BETA,ALPHA0,PHI,OMEGA,P,GAM,G,REQO,REQI,DHXAI,DHXFI,
               *        DHXAO,DHXFO,RATIO,RBALL,RRACE,S,ESTAR,DELTLY,RATIOA,RATIOV
000003       10 Y1=0.025E6*COS(PHI)/(0.025E6-2.08432*HX)
000013          Y2=ACOS(Y1)
000015          Y3=SIN(Y2)
000017          Y4=SIN(PHI)-Y3
000023          Y5=0.025E6*COS(PHI)/(0.025E6-2.08432*RATIO**0.73*HX)
000036          Y6=ACOS(Y5)
000040          Y7=SIN(Y6)
000042          Y8=SIN(PHI)-Y7
000046          Y9=0.025E6*(Y4+Y8)
000050          Y10=HX*Y3
000053          Y11=RATIO**0.73*HX*Y7
000060          Y12=2.08432*(Y10+Y11)
000062          XLY=Y9+Y12
000064          DELTAC=DELTLY-XLY
000067          RETURN
000067          END
```

```
                    FUNCTION DELTAM (HX)
000003              COMMON VIS,XK,BETA,ALPHAO,PHI,OMEGA,P,GAM,G,REQO,REQI,DHXAI,DHXFI,
                   *       DHXAO,DHXFO,RATIO,RHALL,RRACE,S,ESTAR,DELTLY,RATIOA,RATIOV
000003           10 Y1=0.025E6*COS(PHI)/(0.025E6-2.10109*HX)
000013              Y2=ACOS(Y1)
000015              Y3=SIN(Y2)
000017              Y4=SIN(PHI)-Y3
000023              Y5=0.025E6*COS(PHI)/(0.025E6-2.10109*RATIOA**0.54*RATIOV**0.70*HX)
000042              Y6=ACOS(Y5)
000044              Y7=SIN(Y6)
000046              Y8=SIN(PHI)-Y7
000052              Y9=0.025E6*(Y4+Y8)
000054              Y10=HX*Y3
000057              Y11=RATIOA**0.54*RATIOV**0.70*HX*Y7
000070              Y12=2.10109*(Y10+Y11)
000072              XLY=Y9+Y12
000074              DELTAM=DELTLY-XLY
000077              RETURN
000077              END
```

```
                 SUBROUTINE BISECT(X,NX,DX,EPS,IER,FCT)
          C
          C
          C         PURPOSE
          C      ...................................................................
          C            TO SOLVE NONLINEAR EQUATIONS
          C
          C         USAGE
          C            CALL BISECT (X,NX,DX,EPS,IER,FCT)
          C            PARAMETER FCT REQUIRES AN EXTERNAL STATEMENT.
          C
          C         DESCRIPTION OF PARAMETERS
          C            X      - THE STARTING VALUE OF THE SEARCH VARIABLE,
          C                     THE SOLUTION ON RETURN.
          C            NX     - THE NUMBER OF SEARCH INTERVALS.
          C            DX     - THE SEARCH INTERVAL.
          C            EPS    - THE UPPER BOUND OF RELATIVE ERROR.
          C            IER    - A RESULTING ERROR PARAMETER.
          C                     IER = 0, SUCCESSFUL SEARCH.
          C                     IER = 1, NO CHANGE OF SIGN FOUND IN SEARCH RANGE.
          C            FCT    - THE NAME OF THE EXTERNAL FUNCTION SUBPROGRAM USED.
          C
          C         SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
          C            THE EXTERNAL FUNCTION SUBPROGRAM FCT(X) MUST BE CODED BY
          C            THE USER SO THAT FCT(X)=0 AT X=SOLUTION.
          C
          C         METHOD
          C            A SEARCH FOR A CHANGE OF SIGN IS PERFORMED AND WHEN FOUND
          C            THE INTERVAL CONTAINING THE SOLUTION IS CONTINUALLY HALVED.
          C
          C      ...................................................................
          C
000011           IER=0
000011           X0=X
000012           DO 200 IX=1,NX
000014           IF(X.NE.X0) GO TO 100
000016           Z1=FCT(X)
000025           XK1=X0
000026           IF(ABS(Z1)-EPS**2)250,250,190
000033       100 Z0=FCT(X)
000043           IF(Z0*Z1)130,250,140
000046       130 XK2=X
000047           GO TO 150
000050       140 XK1=X
000051           Z1=Z0
000053           GO TO 190
000053       150 X=XK1+0.5*(XK2-XK1)
000057           Z0=FCT(X)
000067           IF(ABS((XK2-XK1)/X)-EPS)250,250,160
000074       160 IF(Z0*Z1)180,250,170
000077       170 XK1=X
000100           Z1=Z0
000102           GO TO 150
000102       180 XK2=X
000103           GO TO 150
000104       190 IF (Z1) 192,250,194
000106       192 X=X-DX
```

```
      GO TO 200
100   X=X+DX
200   CONTINUE
      IER=1
250   RETURN
      END
```

APPENDIX C

SAMPLE PRINTOUT OF TASK II DATA

```
TEST NO.  10
OIL = MARC 14231
BEARING ROUGHNESS =   STD
INITIAL FILM THICKNESS = THICK
LOAD(N)              =    890        LOAD(LB)           =    200
AFT TEMP(C)          =   24.4        AFT TEMP(F)        =   76.0
FWD TEMP(C)          =   25.0        FWD TEMP(F)        =   77.0
PRESSURE(PASCAL)     = 1.013E+05     PRESSURE(TORR)     = 7.600E+02

PRE PUMP DOWN RESULTS

       BASE SPEED(RPM) =  12.0


                                                     FILM THICKNESS(MICROMETERS)

                                AFT BEARING                                                  FORWARD BEARING

                  OUTER CONTACTS                    INNER CONTACTS                 OUTER CONTACTS                  INNER CONTACTS

              BHCAO           BHMAO             BHCAI           BHMAI             BHCFO           BHMFO            BHCFI           BHMFI
               .124            .110              .114            .100              .121            .107             .111            .097
                                                                                                                                                      TORQUE
SPEED(RPM) TCEN    XCEN    TMIN    XMIN      TCEN    XCEN    TMIN    XMIN      TCEN    XCEN    TMIN    XMIN      TCEN    XCEN    TMIN    XMIN         (N-M)
   50.00   .351    .209    .299    .196      .324    .193    .271    .178      .342    .203    .291    .190      .315    .188    .264    .173          .268
  100.00   .582    .335    .485    .323      .537    .309    .441    .293      .567    .326    .473    .314      .523    .301    .430    .285          .381
  150.00   .783    .452    .645    .441      .722    .417    .586    .401      .762    .440    .628    .430      .703    .406    .571    .390          .452
  200.00   .964    .534    .788    .522      .891    .492    .716    .474      .940    .519    .768    .508      .867    .479    .698    .462          .445


                                                     FILM THICKNESS(MICROINCHES)

                                AFT BEARING                                                  FORWARD BEARING

                  OUTER CONTACTS                    INNER CONTACTS                 OUTER CONTACTS                  INNER CONTACTS

              BHCAO           BHMAO             BHCAI           BHMAI             BHCFO           BHMFO            BHCFI           BHMFI
               4.88            4.33              4.50            3.94              4.74            4.22             4.38            3.83
                                                                                                                                                      TORQUE
SPEED(RPM) TCEN    XCEN    TMIN    XMIN      TCEN    XCEN    TMIN    XMIN      TCEN    XCEN    TMIN    XMIN      TCEN    XCEN    TMIN    XMIN         (OZ-IN)
   50.00  13.82    8.23   11.77    7.70     12.76    7.59   10.69    6.99     13.45    8.01   11.46    7.50     12.40    7.39   10.41    6.81          38.0
  100.00  22.92   13.19   19.11   12.70     21.14   12.17   17.36   11.53     22.31   12.84   18.62   12.37     20.57   11.85   16.91   11.23          54.0
  150.00  30.82   17.79   25.39   17.37     28.42   16.41   23.06   15.77     29.99   17.32   24.73   16.92     27.66   15.97   22.45   15.36          64.0
  200.00  38.02   21.01   31.05   20.55     35.06   19.38   28.20   18.66     37.00   20.45   30.25   20.02     34.12   18.85   27.47   18.18          63.0
```

```
TEST NO.  19
OIL = 9APC 36219
BEARING ROUGHNESS =   STD
INITIAL FILM THICKNESS = THICK
LOAD(N)             =   890        LOAD(LB)           =   200
AFT TEMP(C)         =  25.6        AFT TEMP(F)        =  78.0
FWD TEMP(C)         =  26.7        FWD TEMP(F)        =  80.0
PRESSURE(PASCAL) = 1.866E-04       PRESSURE(TORR)     = 1.400E-06


INITIAL AFTER PUMP DOWN RESULTS

      BASE SPEED(RPM) =  14.0


                                                   FILM THICKNESS(MICROMETERS)


                          AFT BEARING                                                    FORWARD BEARING

              OUTER CONTACTS               INNER CONTACTS                OUTER CONTACTS               INNER CONTACTS

             BHCAO         BHMAO         BHCAI         BHMAI          BHCFO         BHMFO         BHCFI         BHMFI
              .131          .116          .121          .106           .124          .111          .115          .100
                                                                                                                              TORQUE
SPEED(RPM) TCEN   XCEN   TMIN   XMIN    TCEN   XCEN   TMIN   XMIN    TCEN   XCEN   TMIN   XMIN    TCEN   XCEN   TMIN   XMIN      (N-M)
   50.00   .333   .173   .284   .158    .307   .159   .258   .144    .315   .164   .270   .150    .291   .151   .245   .137      .148
  100.00   .552   .280   .461   .265    .509   .258   .419   .241    .523   .266   .438   .252    .482   .245   .398   .229      .247
  150.00   .741   .367   .612   .353    .684   .338   .556   .321    .703   .348   .581   .336    .648   .321   .528   .305      .388
  200.00   .915   .408   .749   .395    .844   .376   .680   .359    .867   .387   .711   .375    .800   .357   .646   .341      .360


                                                   FILM THICKNESS(MICROINCHES)


                          AFT BEARING                                                    FORWARD BEARING

              OUTER CONTACTS               INNER CONTACTS                OUTER CONTACTS               INNER CONTACTS

             BHCAO         BHMAO         BHCAI         BHMAI          BHCFO         BHMFO         BHCFI         BHMFI
              5.17          4.58          4.77          4.16           4.90          4.35          4.52          3.95
                                                                                                                              TORQUE
SPEED(RPM) TCEN   XCEN   TMIN   XMIN    TCEN   XCEN   TMIN   XMIN    TCEN   XCEN   TMIN   XMIN    TCEN   XCEN   TMIN   XMIN     (OZ-IN)
   50.00   13.09   6.80  11.17   6.23   12.07   6.28  10.14   5.66   12.41   6.45  10.61   5.92   11.45   5.95   9.64   5.38      21.0
  100.00   21.73  11.04  18.14  10.45   20.02  10.18  16.48   9.49   20.59  10.46  17.24   9.93   18.99   9.65  15.65   9.02      35.0
  150.00   29.19  14.44  24.10  13.91   26.92  13.32  21.89  12.64   27.68  13.70  22.89  13.22   25.53  12.63  20.79  12.01      55.0
  200.00   36.01  16.05  29.47  15.55   33.21  14.81  26.77  14.12   34.15  15.22  28.00  14.77   31.49  14.06  25.43  13.42      51.0
```

```
TEST NO.  10
OIL = MOBC 36233
BEARING ROUGHNESS =   STD
INITIAL FILM THICKNESS = THICK
LOAD(N)            =    890       LOAD(LB)          =    200
AFT TEMP(C)        =   29.4       AFT TEMP(F)       =   85.0
FWD TEMP(C)        =   32.8       FWD TEMP(F)       =   91.0
PRESSURE(PASCAL) = 1.999E-04      PRESSURE(TORR)    = 1.500E-06

24 HOURS AFTER PUMP DOWN

       BASE SPEED(RPM) =  10.0


                                          FILM THICKNESS(MICROMETERS)

                          AFT BEARING                                                    FORWARD BEARING

              OUTER CONTACTS               INNER CONTACTS                 OUTER CONTACTS               INNER CONTACTS

            BMCAO          BMMAO          BMCAI          BMMAI          BMCFO          BMMFO          BMCFI          BMMFI
             .131           .116           .121           .106           .113           .101           .104           .092
                                                                                                                                   TORQUE
SPEED(RPM) TCEN   XCEN   TMIN   XMIN   TCEN   XCEN   TMIN   XMIN   TCEN   XCEN   TMIN   XMIN   TCEN   XCEN   TMIN   XMIN      (N-M)
   50.00   .277   .153   .238   .138   .255   .141   .216   .126   .239   .132   .206   .120   .220   .122   .187   .109       .092
  100.00   .429   .197   .387   .182   .424   .181   .351   .165   .396   .170   .335   .158   .365   .156   .304   .143       .233
  150.00   .618   .287   .513   .272   .570   .265   .466   .247   .532   .247   .445   .236   .491   .228   .404   .219       .508
  200.00   .762   .399   .628   .384   .703   .368   .570   .349   .657   .344   .544   .333   .606   .317   .494   .302       .367


                                          FILM THICKNESS(MICROINCHES)

                          AFT BEARING                                                    FORWARD BEARING

              OUTER CONTACTS               INNER CONTACTS                 OUTER CONTACTS               INNER CONTACTS

            BMCAO          BMMAO          BMCAI          BMMAI          BMCFO          BMMFO          BMCFI          BMMFI
             5.17           4.58           4.77           4.16           4.46           3.97           4.11           3.61
                                                                                                                                   TORQUE
SPEED(RPM) TCEN   XCEN   TMIN   XMIN   TCEN   XCEN   TMIN   XMIN   TCEN   XCEN   TMIN   XMIN   TCEN   XCEN   TMIN   XMIN      (OZ-IN)
   50.00  10.91   6.03   9.37   5.45  10.06   5.56   8.51   4.95   9.40   5.20   8.12   4.72   8.67   4.79   7.38   4.29      13.0
  100.00  16.89   7.75  15.22   7.17  14.68   7.14  13.82   6.52  15.59   6.68  13.19   6.22  14.38   6.14  11.98   5.65      33.0
  150.00  24.32  11.29  20.21  10.71  22.44  10.42  18.36   9.73  20.96   9.74  17.53   9.29  19.33   8.98  15.92   8.63      72.0
  200.00  30.03  15.72  24.72  15.12  27.67  14.50  22.46  13.73  25.86  13.55  21.43  13.11  23.85  12.50  19.47  11.91      52.0
```

APPENDIX D

LISTING OF TASK III DATA REDUCTION PROGRAM

```
          PROGRAM ENDFT (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      C                  *  DATA REDUCTION FOR ENDURANCE  *
      C                  *       OIL FILM THICKNESS       *
      C                  *          JUNE 1975             *
      C                  * * * * * * * * * * * * * * * * *
      C
000003    DIMENSION TIME(100),DELTLV(100),HCAI(100),HMAI(100),HCFI(100),
         1          HMFI(100),HXCAI(100),HXMAI(100),HXCFI(100),HXMFI(100),
         2          HXCAIS(100),HXMAIS(100),HXCFIS(100),HXMFIS(100),
         3          HCAIS(100),HMAIS(100),HCFIS(100),HMFIS(100),BASEN(100),
         4          TORQUE(100),TORQSI(100),PRESS(100),PRESSI(100),
         5          TEMPA(100),TEMPF(100),RHCAI(100),RHMAI(100),
         6          RHCFI(100),RHMFI(100),RHCAIS(100),RHMAIS(100),
         7          RHCFIS(100),RHMFIS(100),NOIL(8)
000003    COMMON VIS,XK,BETA,ALPHAO,PHI,OMEGA,P,GAM,G,REQI,DMXAI,DMXFI,
         *        RATIO,RBALL,RRACE,S,FSTAR,DELTL,RATIOA,RATIOV
000003    EXTERNAL DELTAC,DELTAM
000003  1 CONTINUE
000003    READ (5,1000) NOIL
000011 1000 FORMAT ( 8A10 )
000011    IF (EOF,5) 2,3
000014  2 STOP
000016  3 READ (5,1010) NBEAR,NTRACK,NTEST
000030 1010 FORMAT ( 2A5, I5 )
000030    LINES=60
      C
      C  BEARING GEOMETRY AND MATERIAL (NOTE UNITS ARE CONVERTED TO SI SYSTEM)
      C
000031    RBALL=0.4125*2.54E-2
000032    RRACE=[illegible]*2.54E-2
000034    S=RBALL/RRACE
000035    FSTAR=[illegible]
000037    PHI=[illegible]*3.141592/180.
000040    [illegible]*2.54E-2
000042    READ (5,1020) XLOAD,RPM,NTIME
000054 1020 FORMAT (F8.0,F8.0,I4)
000054    XLOAD=XLOAD*4.448
000056    P=XLOAD/(9.*SIN(PHI))
000062    [illegible](1./3.)
000063    [illegible]
000064    [illegible]E-2
000064    READ (5,1030) A,B,GAM,G,XK,BETA
000103 1030 FORMAT([illegible])
000110    DO 100 I=1,NTIME
000116    READ (5,1040) TEMPA(I),TEMPF(I),TORQUE(I),DELTLV(I),BASEN(I),
         *                  PRESS(I),TIME(I)
000137 1040 FORMAT( 5F10.0, F5.0, 4X, F10.0 )
000137    PRESS(I)=PRESS(I)+14.7
000142    TEMPAS=(TEMPA(I)-32.)*5./9.
000144    TEMPFS=(TEMPF(I)-32.)*5./9.
      C
      C  *BASE CALCULATIONS FOR AFT BEARING
      C
000147    CALL ALPHOP (TEMPAS,A,B,GAM,G,XK,BETA,ALPHAO,VIS)
      C
      C  INNER CONTACTS
      C
      OMEGA=[illegible]*2.*3.14159/60.
      CALL FILM ([illegible])
C
C  FILM THICKNESS CALCULATIONS FOR AFT BEARING
C
C
C  INNER CONTACTS
C
      OMEGA=[illegible]*2.*3.14159/60.
      CALL FILM ([illegible])
      [illegible]
      [illegible]
      [illegible]
C
C  [illegible] CALCULATIONS FOR FORWARD BEARING
C
      CALL FLOROF ([illegible],ALPHAC,VIS)
C
C  INNER CONTACTS
C
      OMEGA=[illegible]*2.*3.14159/60.
      CALL FILM ([illegible])
C
C  FILM THICKNESS CALCULATIONS FOR FORWARD BEARING
C
C  INNER CONTACTS
C
      OMEGA=[illegible]*2.*3.14159/60.
      CALL FILM ([illegible])
      [illegible]
      [illegible]
      [illegible]
      [illegible]
C
C  EXPERIMENTAL FILM THICKNESSES CALCULATED FROM MEASURED BEARING
C  DISPLACEMENT
C
C  FIRST SOLVE FOR INCREMENT IN FILM THICKNESS AT INNER CONTACTS OF AFT
C  BEARING (IN MICROINCHES)
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      CALL [illegible] ([illegible],EPS,IER,DELTAC)
      IF (IER.EQ.0) GO TO 45
   44 WRITE (6,6000)
 6000 FORMAT (//* ERROR- NO CHANGE OF SIGN FOUND IN SEARCH RANGE*)
      STOP
   45 [illegible]
      [illegible]
      [illegible]
      [illegible]
      CALL [illegible] ([illegible],EPS,IER,DELTAM)
      IF (IER.NE.0) GO TO 44
      [illegible]
C
```

```
              C  SOLVE FOR INCREMENT IN FILM THICKNESS FOR INNER CONTACTS OF FORWARD
              C  BEARING BY USING CORRECTION FOR BEARING TEMPERATURE DIFFERENCE
              C
000271             DHXCFI=RATIO**0.73*DHXCAI
000275             DHXMFI=RATIOA**0.54*RATIOV**0.70*DHXMAI
              C
              C  CONVERT FILM THICKNESS INCREMENTS FROM MICROINCHES TO METERS
              C
000305             C1=2.54E-2/1.0E6
000307             DHXCAI=DHXCAI*C1
000310             DHXCFI=DHXCFI*C1
000312             DHXMAI=DHXMAI*C1
000313             DHXMFI=DHXMFI*C1
              C
              C  NONDIMENSIONALIZE FILM THICKNESS INCREMENTS
              C
000314             DHXCAI=DHXCAI/REQI
000315             DHXCFI=DHXCFI/REQI
000316             DHXMAI=DHXMAI/REQI
000317             DHXMFI=DHXMFI/REQI
              C
              C  FILM THICKNESSES IN AFT BEARING (INCREMENT PLUS BASE)
              C
000320             HXCAI(I)=DHXCAI+BHCAI(I)
000323             HXMAI(I)=DHXMAI+BHMAI(I)
              C
              C  FILM THICKNESSES IN FORWARD BEARING (INCREMENT PLUS BASE)
              C
000325             HXCFI(I)=DHXCFI+BHCFI(I)
000327             HXMFI(I)=DHXMFI+BHMFI(I)
              C
              C  CONVERT FILM THICKNESSES FROM DIMENSIONLESS TO MICROMETERS
              C
000332             CI=REQI*1.E6
000333             BHCAIS(I)=BHCAI(I)*CI
000336             BHMAIS(I)=BHMAI(I)*CI
000337             BHCFIS(I)=BHCFI(I)*CI
000341             BHMFIS(I)=BHMFI(I)*CI
000342             HXCAIS(I)=HXCAI(I)*CI
000344             HXMAIS(I)=HXMAI(I)*CI
000345             HXCFIS(I)=HXCFI(I)*CI
000347             HXMFIS(I)=HXMFI(I)*CI
000350             HCAIS(I)=HCAI(I)*CI
000352             HMAIS(I)=HMAI(I)*CI
000353             HCFIS(I)=HCFI(I)*CI
000355             HMFIS(I)=HMFI(I)*CI
              C
              C  CONVERT TORQUE,LOAD,AND TEMPERATURE TO SI UNITS
              C
000356             TORQSI(I)=TORQUE(I)*7.0612E-3
000360             XLOADS=4.448*XLOAD
              C
              C  CONVERT FILM THICKNESSES FROM DIMENSIONLESS TO MICROINCHES
              C
000362             BI=CI*39.37
000364             BHCAI(I)=BHCAI(I)*BI
000366             BHMAI(I)=BHMAI(I)*BI
000370             BHCFI(I)=BHCFI(I)*BI
```

```
000371          BHMFI(I)=BHMFI(I)*BI
000372          HXCAI(I)=HXCAI(I)*BI
000374          HXMAI(I)=HXMAI(I)*BI
000375          HXCFI(I)=HXCFI(I)*BI
000376          HXMFI(I)=HXMFI(I)*BI
000400          HCAI(I)=HCAI(I)*BI
000401          HMAI(I)=HMAI(I)*BI
000402          HCFI(I)=HCFI(I)*BI
000404          HMFI(I)=HMFI(I)*BI
000405          IF(LINE .LT. 60)  GO TO 80
000410          LOAD=10HLOAD(LB) =
000411          WRITE (6,1100) NTEST,NOIL,NBEAR,NTHCK,LOAD,XLOAD,RPM
000433     1100 FORMAT (1H1///* ENDURANCE TEST NO. *,I3/ * OIL = *,8A10/
               *        * BEARING ROUGHNESS = *,A5/* INITIAL OIL FILM THICKNESS = *
               *        A5/1X,A10,F5.0 / * SPEED(RPM) = *,F5.0 /
               *      * CENTRAL OUTER CONTACTS = CENTRAL INNER CONTACTS MULTIPLIED*
               *      * BY 1.08432* /
               *      * MINIMUM OUTER CONTACTS = MINIMUM INNER CONTACTS MULTIPLIED*
               *      * BY 1.10109* )
000433          MICRO=10HINCHES
000434          MPRES=8H  (TORR)
000436          MTORQ=7H(OZ-IN)
000437          MTEMP=3H(F)
000441          WRITE(6,1110) MICRO,MPRES,MTORQ,MTEMP,MTEMP
000457     1110 FORMAT (// 69X,*FILM THICKNESSES ARE IN MICRO*,A10 // 47X,
               *              *AFT BEARING, INNER CONTACT3*,25X,*FORWARD BEARING, IN*
               *              *NER CONTACTS* /1X,*TEST*,19X,*BASE*/1X,*TIME PRESSUR*
               *              *E TORQUE  SPEED*,6X,*TEMPA*,48X,*TEMPF* / 1X,*(HR)*
               *              1X,A8,A7,*  (RPM)*,8X,A3,2X,*BHCAI  XCENI  TCENI  BHMA*
               *              *I  XMINI  TMINI*,8X,A3,2X,*BHCFI  XCENI  TCENI  BHMF*
               *              *I  XMINI  TMINI*  )
000457          LINE=21
000460       80 CONTINUE
000460          WRITE(6,1120) TIME(I),PRESS(I),TORQUE(I),BASEN(I),TEMPA(I),
               1                 BHCAI(I),HXCAI(I),HCAI(I),BHMAI(I),HXMAI(I),HMAI(I),
               2                 TEMPF(I),BHCFI(I),HXCFI(I),HCFI(I),BHMFI(I),
               3                 HXMFI(I),HMFI(I)
000530     1120 FORMAT(1X,F5.0,E8.1,F7.2,F7.2,2(4X,F7.1,6F7.2))
000530          LINE=LINE+1
000532          TEMPA(I)=TEMPAS
000534          TEMPF(I)=TEMPFS
000535      100 CONTINUE
         C
         C      REPEAT PRINTOUT IN S.I. UNITS
         C
000540          LINE=66
000541          DO 150 I=1,NTIME
000542          IF(LINE .LT. 60)  GO TO 140
000544          LOAD=10HLOAD(N) =
000546          WRITE (6,1100) NTEST,NOIL,NBEAR,NTHCK,LOAD,XLOADS,RPM
000567          MICRO=10HMETERS
000570          MPRES=8H(PASCAL)
000572          MTORQ=7H  (N-M)
000573          MTEMP=3H(C)
000575          WRITE(6,1110) MICRO,MPRES,MTORQ,MTEMP,MTEMP
000613          LINE=21
000614      140 CONTINUE
000614          WRITE(6,1130) TIME(I),PRESI(I),TORQSI(I),BASEN(I),TEMPA(I),
                 1              BHCAIS(I),HXCAIS(I),HCAIS(I),BHMAIS(I),HXMAIS(I),
                 2              HMAIS(I),TEMPF(I),BHCFIS(I),HXCFIS(I),HCFIS(I),
                 3              BHMFIS(I),HXMFIS(I),HMFIS(I)
000664       1130 FORMAT(1X,F5.0,E8.1,F7.3,F7.2,2(4X,F7.1,6F7.3))
000664            LINE=LINE+1
000666        150 CONTINUE
000670            GO TO 1
000671            END
```

```
              SUBROUTINE  FLPROP (T,A,B,GAM,G,KK,BETA,ALPHAO,E)
000014        Y=ALOG10(T+273.)
000023        X=A-B*Y
000025        E=10.**(10.**X)-0.6
000035        E=E*(GAM-G*(T-15.6))*0.001
000042        ALPHAO=KK/T**BETA
000047        RETURN
000050        END
```

```
              SUBROUTINE FILM (REQ,A,HC,HM)
000007        COMMON VIS,XK,BETA,ALPHAO,PHI,OMEGA,P,GAM,G,REQI,DHXAI,DHXFI,
             *       RATIO,RBALL,RRACE,S,ESTAR,DELTL,RATIDA,RATIOV
          C
          C   CALCULATE DIMENSIONLESS CENTRAL-REGION FILM THICKNESS
          C
000007        X1=(1.+2.*S*COS(PHI))/(2.*S*(1.+S*COS(PHI)))
000022        X2=(VIS*2.*RBALL*X1*OMEGA)/(ESTAR*REQ)
000033        X3=X2**0.73
000037        X4=(ALPHAO*ESTAR)
000041        X5=X4**0.73
000044        X6=3.*P/(4.*A*ESTAR*REQ)
000050        X7=X6**0.09
000054        HC=1.18*X5*X3/X7
          C
          C   CALCULATE DIMENSIONLESS MINIMUM FILM THICKNESS
          C
000057        X8=X2**0.70
000061        X9=X4**0.54
000067        X10=X6**0.13
000073        HM=1.64*X9*X8/X10
000077        RETURN
000077        END
```

```
                  FUNCTION DELTAC (MX)
000003            COMMON VIS,XK,BETA,ALPHAO,PHI,OMEGA,P,GAM,G,HFOI,OHXAI,OHKFI,
                 *       RATIO,BALL,DRAFT,S,ESTAN,DELTLV,RATIOA,RATIOV
000003         10 V1=0.025E6*COS(PHI)/(0.025E6-2.08432*MX)
000011            V2=ACOS(V1)
000015            V3=SIN(V2)
000017            V4=SIN(PHI)-V3
000023            V5=0.025E6*COS(PHI)/(0.025E6-2.08432*RATIO**0.73*MX)
000036            V6=ACOS(V5)
000040            V7=SIN(V6)
000042            V8=SIN(PHI)-V7
000046            V9=0.025E6*(V4+V8)
000050            V10=MX*V3
000051            V11=RATIO**0.73*MX*V7
000060            V12=2.08432*(V10+V11)
000062            XLV=V9+V12
000064            DELTAC=DELTLV-XLV
000067            RETURN
000067            END
```

```
000003          FUNCTION DELTAM (MX)
000003          COMMON VIS,XK,BETA,ALPHAO,PHI,OMEGA,P,GAM,G,REQI,OMXAI,OMXFI,
               *       RATIO,WWALL,WRACE,S,ESTAR,DELTLV,RATIOA,RATIOV
000003       10 V1=0.025E6*COS(PHI)/(0.025E6-2.10109*MX)
000011          V2=ACOS(V1)
000015          V3=SIN(V2)
000017          V4=SIN(PHI)-V3
000023          V5=0.025E6*COS(PHI)/(0.025E6-2.10109*RATIOA**0.54*RATIOV**0.70*MX)
000042          V6=ACOS(V5)
000044          V7=SIN(V6)
000046          V8=SIN(PHI)-V7
000052          V9=0.025E6*(V4+V8)
000054          V10=MX*V4
000057          V11=RATIOA**0.54*RATIOV**0.70*MX*V7
000070          V12=2.10109*(V10+V11)
000072          XLV=V9+V12
000074          DELTAM=DELTLV-XLV
000077          RETURN
000077          END
```

```
                 SUBROUTINE BISECT(X,NX,DX,EPS,IER,FCT)
             C
             C
             C      PURPOSE
             C         TO SOLVE NONLINEAR EQUATIONS
             C
             C   ..............................................................
             C
             C      USAGE
             C         CALL BISECT (X,NX,DX,EPS,IER,FCT)
             C         PARAMETER FCT REQUIRES AN EXTERNAL STATEMENT.
             C
             C      DESCRIPTION OF PARAMETERS
             C         X      - THE STARTING VALUE OF THE SEARCH VARIABLE.
             C                  THE SOLUTION ON RETURN.
             C         NX     - THE NUMBER OF SEARCH INTERVALS.
             C         DX     - THE SEARCH INTERVAL.
             C         EPS    - THE UPPER BOUND OF RELATIVE ERROR.
             C         IER    - A RESULTING ERROR PARAMETER.
             C                  IER = 0, SUCCESSFUL SEARCH.
             C                  IER = 1, NO CHANGE OF SIGN FOUND IN SEARCH RANGE.
             C         FCT    - THE NAME OF THE EXTERNAL FUNCTION SUBPROGRAM USED.
             C
             C      SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
             C         THE EXTERNAL FUNCTION SUBPROGRAM FCT(X) MUST BE CODED BY
             C         THE USER SO THAT FCT(X)=0 AT X=SOLUTION.
             C
             C      METHOD
             C         A SEARCH FOR A CHANGE OF SIGN IS PERFORMED AND WHEN FOUND
             C         THE INTERVAL CONTAINING THE SOLUTION IS CONTINUALLY HALVED.
             C
             C   ..............................................................
             C
000011           IER=0
000011           X0=X
000012           DO 200 I=1,NX
000014           IF(X.NE.X0) GO TO 100
000016           Z1=FCT(X)
000025           XX1=X0
000026           IF(ABS(Z1)-EPS**2)250,250,190
000031       100 Z2=FCT(X)
000033           IF(Z2*Z1)130,250,140
000036       130 XX2=X
000047           GO TO 150
000050       140 XX1=X
000051           Z1=Z2
000053           GO TO 190
000054       150 X=XX1+0.5*(XX2-XX1)
000057           Z2=FCT(X)
000067           IF(ABS((XX2-XX1)/X)-EPS)250,250,160
000074       160 IF(Z2*Z1)180,250,170
000077       170 XX1=X
000100           Z1=Z2
000102           GO TO 150
000102       180 XX2=X
000103           GO TO 150
000104       190 IF (Z1) 192,250,194
000106       192 X=X-DX
```

```
000112          GO TO 240
000113     190  IER=0
000114     240  CONTINUE
000115          IER=1
000116     250  RETURN
000117          END
```

APPENDIX E

TASK III DATA

```
ENDURANCE TEST NO.    1
OIL = APIEZON A    +ANTI +LEAD NAPH
BEARING ROUGHNESS = ROUGH
INITIAL OIL FILM THICKNESS = THICK
LOAD(N) =   890
SPEED(RPM) =   100
CENTRAL OUTER CONTACTS = CENTRAL INNER CONTACTS MULTIPLIED BY 1.08432
MINIMUM OUTER CONTACTS = MINIMUM INNER CONTACTS MULTIPLIED BY 1.10104

                                                             FILM THICKNESSES ARE IN MICROMETERS

                                             AFT BEARING, INNER CONTACTS                                  FORWARD BEARING, INNER CONTACTS

TEST                        BASE
TIME PRESSURE  TORQUE      SPEED      TEMPA                                                    TEMPF
(HR) (PASCAL)   (N-M)      (RPM)       (C)   BMCAI  XCENI  TCENI  BMMAI  XMINI  THINI        (C)   BMCFI  XCENI  TCENI  BMMFI  XMINI  THINI
   0 1.3E-04    .205       21.00       25.0   .062   .062   .192   .055   .055   .163        25.0   .062   .062   .192   .055   .055   .163
   2 1.4E-04    .141       18.00       26.1   .052   .052   .182   .047   .047   .155        27.2   .049   .049   .173   .045   .045   .148
   6 1.6E-04    .115       18.00       27.2   .049   .049   .173   .045   .045   .148        28.9   .046   .046   .160   .041   .041   .138
  24 2.1E-04    .044       24.00       27.8   .063   .063   .168   .056   .056   .144        30.0   .057   .057   .152   .051   .051   .132
  30 1.6E-04    .106       24.00       28.3   .058   .058   .164   .052   .052   .141        30.0   .054   .054   .152   .048   .048   .132
  48 1.6E-04    .085       26.00       27.8   .063   .063   .168   .056   .056   .144        29.4   .058   .058   .156   .052   .052   .135
  76 1.3E-04    .111       20.00       27.8   .059   .087   .168   .053   .081   .144        29.4   .055   .081   .156   .050   .075   .135
 144 1.1E-04    .106       25.00       27.8   .061   .097   .168   .055   .090   .144        28.9   .058   .092   .160   .052   .086   .138
 168 1.2E-04    .111       20.00       27.2   .053   .073   .173   .048   .067   .148        29.4   .048   .066   .156   .044   .061   .135
 192 1.0E-04    .099       25.00       28.3   .060   .091   .164   .053   .084   .141        31.1   .053   .080   .145   .048   .075   .126
 216 1.3E-04    .111       18.00       28.9   .046   .074   .160   .041   .069   .138        31.1   .041   .067   .145   .038   .063   .126
 240 1.2E-04    .120       28.00       31.1   .057   .088   .145   .052   .082   .126        33.3   .052   .080   .131   .047   .075   .115
 312 1.1E-04    .111       22.00       30.6   .049   .094   .148   .045   .089   .129        32.8   .045   .085   .135   .041   .081   .118
 336 1.3E-04    .078       27.00       28.9   .061   .098   .160   .055   .091   .138        31.1   .056   .089   .145   .050   .083   .126
 360 1.2E-04    .074       24.00       28.3   .058   .089   .164   .052   .082   .141        30.6   .052   .080   .148   .047   .075   .129
 384 1.2E-04    .078       18.00       27.8   .048   .071   .168   .043   .066   .144        30.6   .042   .062   .148   .039   .059   .129
 456 9.5E-05    .092       29.00       27.2   .070   .115   .173   .062   .106   .148        29.4   .063   .104   .156   .057   .097   .135
 480 1.1E-04    .071       21.00       27.8   .054   .090   .168   .048   .085   .144        30.0   .049   .082   .152   .044   .077   .132
 504 1.1E-04    .076       22.00       27.8   .056   .092   .168   .050   .086   .144        30.0   .050   .083   .152   .046   .078   .132
 528 9.1E-05    .092       24.00       26.7   .072   .132   .177   .064   .123   .152        29.4   .063   .116   .156   .057   .109   .135
 552 8.8E-05    .082       18.00       27.2   .049   .095   .173   .045   .089   .148        30.0   .043   .084   .152   .040   .079   .132
 624 8.7E-05    .071       19.00       27.8   .070   .107   .168   .062   .099   .144        31.1   .060   .092   .145   .054   .086   .126
 672 9.1E-05    .078       15.00       27.2   .043   .083   .173   .039   .079   .148        30.0   .038   .073   .152   .035   .070   .132
 720 8.0E-05    .056       27.00       28.3   .063   .100   .164   .056   .092   .141        30.6   .057   .090   .148   .051   .084   .129
 792 8.4E-05    .071       12.00       28.9   .034   .051   .160   .031   .048   .136        32.8   .029   .043   .135   .027   .041   .118
 840 7.7E-05    .045       22.00       26.7   .059   .098   .177   .053   .091   .152        28.3   .054   .090   .164   .049   .085   .141
 888 7.6E-05    .085       25.00       27.8   .061   .107   .168   .055   .100   .144        30.6   .054   .094   .148   .049   .089   .129
 936 7.2E-05    .071       19.00       30.0   .045   .085   .152   .041   .080   .132        32.8   .040   .075   .135   .037   .072   .118
1014 8.0E-05    .111       12.00       28.9   .034   .048   .160   .031   .045   .138        32.2   .029   .042   .138   .027   .040   .120
1066 6.7E-05    .071       21.00       27.8   .058   .108   .168   .052   .101   .144        30.0   .052   .097   .152   .047   .092   .132
1118 6.7E-05    .120       21.00       27.8   .058   .102   .168   .052   .095   .144        29.4   .053   .094   .156   .048   .089   .135
1166 7.3E-05    .106       24.00       26.1   .064   .116   .182   .057   .108   .155        28.9   .056   .101   .160   .051   .095   .138
1234 6.7E-05    .092       17.00       28.3   .045   .104   .164   .041   .099   .141        30.6   .041   .094   .148   .037   .090   .129
1296 6.7E-05    .085       21.00       27.8   .054   .104   .168   .048   .098   .144        29.4   .050   .096   .156   .045   .091   .135
1354 5.3E-05    .099       19.00       30.0   .045   .104   .152   .041   .099   .132        32.2   .041   .094   .138   .038   .091   .120
1402 6.0E-05    .111       24.00       31.7   .050   .111   .141   .045   .106   .123        33.3   .046   .103   .131   .042   .099   .115
1488 6.0E-05    .092       16.00       35.0   .032   .077   .123   .030   .074   .108        37.2   .029   .070   .112   .028   .068   .099
1560 5.8E-05    .035       22.00       30.0   .050   .104   .152   .046   .099   .132        32.8   .045   .092   .135   .041   .088   .118
1642 4.8E-05    .085       17.00       30.6   .041   .084   .148   .037   .080   .129        31.7   .039   .080   .141   .036   .077   .123
```

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ENDURANCE TEST NO.   1
OIL =  APIEZON A     +ANTI +LEAD NAPH
BEARING ROUGHNESS = ROUGH
INITIAL OIL FILM THICKNESS = THICK
LOAD(N) =   888
SPEED(RPM) =   130
CENTRAL OUTER CONTACTS = CENTRAL INNER CONTACTS MULTIPLIED BY 1.00432
MINIMUM OUTER CONTACTS = MINIMUM INNER CONTACTS MULTIPLIED BY 1.10109

                                                                  FILM THICKNESSES ARE IN MICROMETERS

                                                AFT BEARING, INNER CONTACTS                                      FORWARD BEARING, INNER CONTACTS
TEST                             BASE
TIME  PRESSURE   TORQUE  SPEED       TEMPA                                                      TEMPF
(MIN) (PASCAL)   (N-M)   (RPM)        (C)   OHCAI  XCENI  TCENI  AHMAI  XMINI  TMINI            (C)   HHCFI  XCENI  TCENI  HMMFI  XMINI  TMINI
 1728  9.72E-05   .044   16.40        28.9   .042   .091   .160   .038   .087   .138            30.0   .040   .087   .152   .036   .083   .132
 1808  9.54E-05   .071   18.30        26.7   .051   .101   .177   .046   .096   .152            28.9   .046   .091   .160   .041   .087   .138
 1866  1.33E-05   .092   22.00        27.2   .057   .120   .173   .051   .114   .148            30.6   .049   .103   .148   .045   .094   .129
 2009  9.7 E-05   .136   24.00        26.7   .063   .121   .177   .656   .114   .152            28.9   .056   .109   .160   .051   .104   .138
 2160  1.74E-05   .044   16.00        26.1   .048   .132   .182   .043   .126   .155            28.3   .043   .119   .164   .039   .115   .141
 2304  1.46E-05   .085   19.00        26.1   .054   .131   .182   .049   .124   .155            28.9   .048   .115   .160   .043   .110   .138
 2409  1.27E-05   .092   18.00        27.2   .044   .111   .173   .045   .106   .148            29.4   .045   .100   .156   .041   .096   .135
 2446  1.54E-05   .120   14.00        27.2   .041   .145   .173   .037   .140   .148            29.4   .037   .131   .156   .034   .127   .135
 2564  9.04E-05   .111   17.00        28.9   .044   .141   .168   .048   .136   .138            30.6   .041   .131   .148   .037   .123   .129
 2688  1.25E-05   .106   24.00        26.7   .063   .175   .177   .056   .146   .152            28.9   .056   .150   .160   .051   .151   .138
 2848  1.04E-05   .106   13.00        27.2   .039   .106   .173   .035   .102   .148            29.4   .035   .096   .154   .032   .093   .135
 2940  2.7E-05    .110   19.00        25.6   .045   .164   .187   .040   .158   .159            27.2   .041   .151   .173   .037   .147   .148
 3048  2.94E-05   .092   11.00        27.8   .038   .117   .168   .035   .108   .144            28.9   .036   .106   .140   .033   .103   .138
 3192  2.94E-05   .094   21.30        26.1   .042   .145   .182   .056   .138   .155            27.8   .058   .134   .148   .052   .124   .144
 3316  2.84E-05   .113   19.00        27.2   .051   .147   .173   .046   .141   .148            28.3   .049   .140   .164   .044   .135   .141
 3528  2.94E-05   .186   27.00        27.2   .066   .150   .173   .059   .141   .148            28.9   .061   .138   .160   .055   .132   .138
 3816  2.94E-05   .070   22.00        26.7   .059   .138   .177   .053   .131   .152            27.8   .056   .131   .168   .050   .125   .144
```

ENDURANCE TEST NO. 1
OIL = APIEZON C [illegible] BLEND NAPH
BEARING ROUGHNESS = ROUGH
INITIAL OIL FILM THICKNESS = THICK
LOAD(LB) = 240
SPEED(RPM) = 240
CENTRAL OUTER CONTACTS = CENTRAL INNER CONTACTS MULTIPLIED BY 1.08032
MINIMUM OUTER CONTACTS = MINIMUM INNER CONTACTS MULTIPLIED BY 1.10109

FILM THICKNESSES ARE IN MICROINCHES

				AFT BEARING, INNER CONTACTS							FORWARD BEARING, INNER CONTACTS						
TEST TIME (HR)	PRESSURE (TORR)	TORQUE (OZ-IN)	BASE SPEED (RPM)	TEMP (F)	HMCAI	HCENI	TCENI	HMMAI	HMINI	TMINI	TEMP (F)	HMCFI	HCENI	TCENI	HMMFI	HMINI	TMINI
0	9.4E-07	20.00	21.00	77.0	2.43	2.43	7.60	2.16	2.16	6.43	77.0	2.43	2.43	7.58	2.16	2.16	6.43
2	1.4E-06	20.00	18.00	79.0	2.05	2.05	7.10	1.89	1.89	6.12	81.0	1.95	1.95	6.80	1.75	1.75	5.83
6	1.2E-06	16.00	18.00	81.0	1.95	1.95	6.80	1.75	1.75	5.83	84.0	1.80	1.80	6.29	1.63	1.63	5.42
20	1.4E-06	17.00	20.00	82.0	2.48	2.48	6.63	2.21	2.21	5.69	86.0	2.29	2.29	5.98	2.02	2.07	5.18
30	1.2E-06	15.00	21.00	83.0	2.28	2.28	6.46	2.09	2.09	5.55	86.0	2.11	2.11	5.98	1.91	1.91	5.18
44	1.2E-06	12.00	25.00	82.0	2.48	2.48	6.63	2.21	2.21	5.69	85.0	2.30	2.30	6.14	2.06	2.06	5.30
76	1.8E-06	16.00	20.00	82.0	2.34	3.43	6.63	2.09	3.17	5.69	85.0	2.17	3.17	6.14	1.95	2.96	5.30
100	1.8E-06	15.00	25.00	82.0	2.41	3.81	6.63	2.15	3.55	5.69	84.0	2.29	3.62	6.29	2.06	3.38	5.42
148	9.8E-07	15.00	20.00	81.0	2.10	2.88	6.80	1.89	2.65	5.83	85.0	1.90	2.59	6.14	1.72	2.41	5.30
192	1.2E-06	14.00	25.00	85.0	2.35	3.57	6.46	2.10	3.32	5.55	88.0	2.07	3.15	5.70	1.87	2.96	4.95
216	9.4E-07	14.00	14.00	84.0	1.80	2.91	6.29	1.63	2.72	5.42	88.0	1.63	2.64	5.70	1.49	2.48	4.95
240	8.7E-07	17.00	20.00	88.0	2.25	3.46	5.70	2.03	3.23	4.95	92.0	2.09	3.15	5.17	1.86	2.95	4.53
312	8.2E-07	16.00	22.00	87.0	1.91	3.70	5.84	1.75	3.50	5.06	91.0	1.75	3.35	5.30	1.60	3.20	4.63
336	1.1E-06	11.00	21.00	84.0	2.42	3.85	6.29	2.17	3.59	5.42	88.0	2.19	3.48	5.70	1.98	3.27	4.95
364	8.8E-07	11.00	20.00	83.0	2.28	3.49	6.46	2.04	3.24	5.55	87.0	2.06	3.16	5.84	1.86	2.95	5.06
388	8.4E-07	11.00	18.00	82.0	1.90	2.79	6.63	1.71	2.59	5.69	87.0	1.67	2.46	5.84	1.52	2.31	5.06
456	7.1E-07	13.00	20.00	81.0	2.76	4.53	6.80	2.45	4.19	5.83	85.0	2.49	4.08	6.14	2.23	3.81	5.30
480	8.4E-07	10.00	21.00	82.0	2.12	3.56	6.63	1.91	3.31	5.69	86.0	1.92	3.22	5.98	1.74	3.03	5.18
504	4.4E-07	11.00	22.00	82.0	2.19	3.63	6.63	1.97	3.39	5.69	86.0	1.98	3.28	5.98	1.79	3.09	5.18
528	7.4E-07	11.00	20.00	80.0	2.83	5.18	6.99	2.51	4.82	5.97	85.0	2.49	4.55	6.14	2.23	4.28	5.30
552	6.4E-07	13.00	18.00	81.0	1.95	3.78	6.80	1.75	3.52	5.83	86.0	1.71	3.29	5.98	1.56	3.13	5.18
624	6.5E-07	10.00	18.00	82.0	2.75	4.22	6.63	2.45	3.90	5.69	88.0	2.37	3.63	5.70	2.13	3.39	4.95
648	5.8E-07	11.00	15.00	81.0	1.78	3.27	6.80	1.59	3.09	5.83	86.0	1.40	2.88	5.98	1.27	2.75	5.18
720	6.4E-07	8.00	21.00	83.0	2.48	3.92	6.46	2.22	3.69	5.55	87.0	2.29	3.55	5.84	2.02	3.37	5.06
792	6.6E-07	10.00	14.00	84.0	1.38	2.02	6.29	1.23	1.91	5.42	91.0	[illegible]	1.70	5.30	1.05	1.63	4.63
800	5.8E-07	12.00	22.00	80.0	2.31	3.80	6.99	2.07	3.58	5.97	83.0	2.19	3.55	6.46	1.92	3.33	5.55
840	5.6E-07	12.00	25.00	82.0	2.41	4.20	6.63	2.15	3.92	5.69	87.0	2.12	3.70	5.84	1.92	3.49	5.06
888	6.4E-07	30.00	19.00	86.0	1.78	3.39	5.98	1.62	3.16	5.18	91.0	1.58	2.96	5.30	1.45	2.82	4.63
1010	6.4E-07	16.00	12.00	84.0	1.38	1.90	6.29	1.23	1.79	5.42	90.0	1.15	1.64	5.43	1.07	1.56	4.74
1056	5.4E-07	10.00	23.00	82.0	2.27	4.25	6.63	2.03	4.00	5.69	86.0	2.05	4.04	5.98	1.85	3.69	5.18
1116	5.8E-07	13.00	21.00	82.0	2.27	4.01	6.63	2.03	3.76	5.69	85.0	2.10	3.71	6.14	1.89	3.50	5.30
1176	5.8E-07	15.00	20.00	79.0	2.53	4.55	7.10	2.25	4.29	6.12	84.0	2.22	3.99	6.29	2.00	3.76	5.42
1236	5.8E-07	11.00	17.00	83.0	1.77	4.00	6.46	1.61	3.90	5.55	87.0	1.60	3.69	5.84	1.46	3.56	5.06
1296	5.4E-07	12.00	21.00	82.0	2.12	4.08	6.63	1.91	3.86	5.69	85.0	1.96	3.78	6.14	1.78	3.59	5.30
1354	4.4E-07	7.00	19.00	86.0	1.79	4.09	5.98	1.62	3.91	5.18	90.0	1.61	3.71	5.43	1.48	3.56	4.74
1402	4.5E-07	15.00	20.00	89.0	1.96	4.35	5.56	1.78	4.15	4.89	92.0	1.83	4.05	5.17	1.67	3.89	4.53
1488	4.5E-07	13.00	16.00	95.0	1.27	3.02	4.83	1.18	2.91	4.25	94.0	1.16	2.76	4.91	1.08	2.68	4.31
1560	4.8E-07	5.00	22.00	86.0	1.98	4.18	5.98	1.79	3.89	5.18	91.0	1.75	3.63	5.30	1.60	3.49	4.63
1632	1.0E-07	12.00	17.00	87.0	1.60	3.32	5.84	1.46	3.17	5.06	89.0	1.52	3.17	5.56	1.40	3.03	4.89

ENDURANCE TEST NO. [illegible]
OIL = SPITZEN 6 [illegible]
BEARING ROUGHNESS = [illegible]
INITIAL OIL FILM THICKNESS = THICK
LOAD(LB) = [illegible]
SPEED(RPM) = 100
CENTRAL OUTER CONTACTS = CENTRAL INNER CONTACTS MULTIPLIED BY 1.08932
MINIMUM OUTER CONTACTS = MINIMUM INNER CONTACTS MULTIPLIED BY 1.10109

FILM THICKNESSES ARE IN MICROINCHES

TEST TIME (HR)	PRESSURE [illegible]	TORQUE (OZ-IN)	BASE SPEED (RPM)	AFT BEARING, INNER CONTACTS							FORWARD BEARING, INNER CONTACTS						
				TEMPA (F)	HMCAI	HCENI	TCENI	HMWAI	HMINI	TMINI	TEMPF (F)	HMCFI	HCENI	TCENI	HMWFI	HMINI	TMINI
1920	1.55E+07	19.80	16.00	84.0	1.65	3.59	6.89	1.50	3.92	5.92	86.0	1.57	3.91	5.94	1.44	3.27	5.10
1990	1.95E+07	18.80	19.00	88.0	2.08	3.78	6.99	1.80	3.76	5.97	84.0	1.80	3.59	6.29	1.63	3.42	5.42
1996	2.85E+07	13.80	22.00	81.0	2.25	4.74	6.80	2.02	4.97	6.03	87.0	1.93	4.07	5.84	1.75	4.08	5.06
2000	1.24E+07	19.00	20.00	80.0	2.46	4.78	6.99	2.20	4.99	5.97	84.0	2.22	4.31	6.29	2.00	4.60	5.42
2100	2.45E+07	14.80	16.00	79.0	1.84	5.19	7.18	1.70	4.97	6.12	83.0	1.69	4.67	6.46	1.54	4.51	5.55
2170	2.77E+07	12.80	19.00	79.0	2.13	5.15	7.10	1.91	4.89	6.12	84.0	1.87	4.52	6.29	1.70	4.34	5.42
2200	2.05E+07	13.00	18.00	81.0	1.95	4.18	6.80	1.75	4.17	5.83	85.0	1.76	3.95	6.19	1.60	3.74	5.30
2296	2.85E+07	17.00	19.00	81.0	1.62	6.76	6.80	1.97	5.51	5.83	85.0	1.46	5.14	6.19	1.34	5.02	5.30
2500	1.85E+07	16.80	17.00	84.0	1.73	5.59	6.89	1.67	5.35	5.92	87.0	1.60	5.14	5.84	1.46	4.44	5.06
2600	2.95E+07	15.80	24.00	80.0	2.46	6.50	6.99	2.20	6.56	5.97	84.0	2.22	6.22	6.29	2.00	5.96	5.42
[illegible]	1.55E+07	15.80	13.00	81.0	1.53	4.18	6.80	1.40	4.02	5.83	85.0	1.38	3.77	6.19	1.27	3.64	5.30
2900	2.85E+07	19.00	19.00	78.0	1.76	6.46	7.37	1.58	6.21	6.27	81.0	1.62	5.96	6.80	1.47	5.77	5.83
3004	2.21E+07	13.80	14.00	82.6	1.49	4.41	6.63	1.36	4.24	5.69	84.0	1.42	4.19	6.29	1.30	4.05	5.42
3192	2.24E+07	14.00	21.00	79.0	2.45	5.73	7.10	2.19	5.92	6.12	82.0	2.27	5.29	6.63	2.03	5.00	5.69
3316	2.14E+07	16.85	19.00	81.0	2.07	5.88	6.80	1.82	5.56	5.83	83.0	1.92	5.51	6.46	1.74	5.30	5.55
3520	1.85E+07	15.80	27.00	81.0	2.62	5.89	6.80	2.33	5.56	5.83	84.0	2.42	5.95	6.29	2.17	5.18	5.42
3816	2.26E+07	11.80	22.00	80.0	2.31	5.45	6.99	2.07	5.16	5.97	82.0	2.19	5.37	6.63	1.97	4.92	5.69

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ENDURANCE TEST NO.   2
OIL =  APIEZON A     +ANTI +LEAD NAPH
BEARING ROUGHNESS =   STD
INITIAL OIL FILM THICKNESS = THICK
LOAD(N) =    890
SPEED(RPM) =   100
CENTRAL OUTER CONTACTS = CENTRAL INNER CONTACTS MULTIPLIED BY 1.08432
MINIMUM OUTER CONTACTS = MINIMUM INNER CONTACTS MULTIPLIED BY 1.10109

                                               FILM THICKNESSES ARE IN MICROMETERS

                                  AFT BEARING, INNER CONTACTS                              FORWARD BEARING, INNER CONTACTS
TEST                    BASE
TIME PRESSURE TORQUE   SPEED      TEMPA                                               TEMPF
(HR) (PASCAL)  (N-M)   (RPM)       (C)   BHCAI  XCENI  TCENI  BHMAI  XMINI  TMINI      (C)   BHCFI  XCENI  TCENI  BHMFI  XMINI  TMINI
   0 1.3E-04    .292   24.00      25.0   .068   .095   .192   .060   .087   .163      25.0   .068   .095   .192   .060   .087   .163
   2 1.3E-04    .191   28.00      25.6   .074   .109   .187   .065   .100   .159      26.1   .072   .106   .182   .064   .098   .155
   6 1.6E-04    .205   15.00      27.2   .043   .065   .173   .039   .061   .148      28.9   .040   .061   .160   .037   .057   .138
  24 2.1E-04    .233   23.00      28.3   .056   .090   .164   .050   .084   .141      30.6   .051   .081   .148   .046   .076   .129
  30 1.6E-04    .169   30.00      28.3   .068   .105   .164   .061   .097   .141      30.6   .062   .095   .148   .055   .088   .129
  48 1.6E-04    .134   21.00      27.8   .054   .076   .168   .048   .071   .144      30.0   .049   .069   .152   .044   .064   .132
  76 1.3E-04    .177   18.00      27.8   .048   .079   .168   .043   .074   .144      30.0   .043   .071   .152   .040   .067   .132
 144 1.3E-04    .169   40.00      28.3   .084   .143   .164   .074   .133   .141      30.6   .076   .129   .148   .068   .121   .129
 168 1.2E-04    .162   28.00      27.8   .066   .092   .168   .059   .085   .144      31.1   .057   .079   .145   .052   .074   .126
 192 1.5E-04    .191   26.00      28.9   .060   .108   .160   .054   .101   .138      31.7   .053   .095   .141   .048   .090   .123
 216 1.3E-04    .177   28.00      29.4   .062   .104   .156   .055   .097   .135      31.7   .056   .094   .141   .050   .088   .123
 288 1.2E-04    .148   26.00      31.1   .054   .108   .145   .049   .102   .126      33.9   .048   .096   .128   .044   .092   .113
 312 1.1E-04    .177   30.00      30.6   .062   .115   .148   .055   .108   .129      32.8   .056   .104   .135   .051   .098   .118
 336 1.3E-04    .120   36.00      28.3   .078   .138   .164   .069   .128   .141      31.1   .069   .121   .145   .061   .114   .126
 360 1.2E-04    .127   36.00      28.3   .078   .120   .164   .069   .111   .141      30.6   .070   .108   .148   .063   .101   .129
 385 1.2E-04    .162   30.00      27.8   .070   .130   .168   .062   .121   .144      30.6   .062   .114   .148   .055   .108   .129
 456 9.5E-05    .162   27.00      27.8   .065   .099   .168   .058   .092   .144      31.1   .056   .085   .145   .050   .080   .126
 480 1.1E-04    .134   30.00      27.8   .070   .123   .168   .062   .115   .144      30.0   .063   .111   .152   .057   .105   .132
 504 1.1E-04    .141   10.00      26.7   .033   .086   .177   .030   .083   .152      28.3   .031   .079   .164   .028   .072   .141
 528 9.3E-05    .141   28.00      26.1   .072   .125   .182   .064   .116   .155      27.8   .066   .115   .168   .059   .108   .144
 552 8.8E-05    .148   29.00      26.7   .072   .173   .177   .064   .163   .152      28.9   .065   .155   .160   .058   .149   .138
 624 8.7E-05    .141   39.00      27.2   .087   .182   .173   .077   .171   .148      29.4   .078   .165   .156   .070   .156   .135
 672 9.1E-05    .113   24.00      27.2   .061   .104   .173   .054   .097   .148      30.0   .054   .091   .152   .048   .086   .132
 720 8.8E-05    .134   30.00      28.9   .066   .139   .160   .059   .131   .138      31.1   .060   .126   .145   .054   .120   .126
 792 8.8E-05    .134   32.00      27.8   .073   .109   .168   .065   .100   .144      32.2   .060   .089   .138   .054   .083   .120
 840 7.7E-05    .155   36.00      27.2   .082   .161   .173   .072   .150   .148      29.4   .074   .145   .156   .066   .136   .135
 888 7.5E-05    .106   28.00      27.8   .066   .141   .168   .059   .133   .144      31.1   .057   .121   .145   .052   .116   .126
 920 7.2E-05    .141   30.00      30.0   .063   .131   .152   .057   .124   .132      32.8   .056   .116   .135   .051   .111   .118
1018 8.0E-05    .184   31.00      28.3   .070   .149   .164   .062   .141   .141      31.1   .062   .132   .145   .055   .125   .126
1066 6.7E-05    .141   36.00      27.8   .077   .156   .168   .068   .147   .144      30.6   .067   .138   .148   .060   .130   .129
1138 6.7E-05    .134   19.00      26.7   .053   .156   .177   .047   .150   .152      28.9   .048   .141   .160   .043   .134   .138
1186 7.7E-05    .141   19.00      26.1   .054   .150   .182   .049   .143   .155      28.3   .049   .135   .164   .044   .130   .141
1234 6.7E-05    .134   22.00      28.9   .053   .148   .160   .048   .142   .138      31.1   .048   .134   .145   .044   .129   .126
1306 6.7E-05    .148   25.00      27.8   .061   .168   .168   .055   .159   .144      31.1   .053   .144   .145   .048   .139   .126
1354 5.3E-05    .099   25.00      30.0   .055   .160   .152   .050   .154   .132      32.8   .049   .142   .135   .045   .137   .118
1402 6.0E-05    .113   25.00      32.2   .050   .129   .138   .046   .124   .120      35.0   .045   .115   .123   .041   .111   .108
1488 6.0E-05    .120   20.00      35.0   .038   .143   .123   .035   .138   .108      37.8   .034   .127   .110   .032   .124   .097
1560 5.3E-05    .120   24.00      30.0   .054   .127   .152   .048   .121   .132      32.8   .047   .113   .135   .043   .108   .118
1632 4.8E-05    .085   29.00      29.4   .063   .160   .156   .057   .152   .135      32.2   .056   .141   .138   .051   .135   .120
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ENDURANCE TEST NO.   2
OIL =  APIEZON A     +ANTI +LEAD NAPH
BEARING ROUGHNESS =    STD
INITIAL OIL FILM THICKNESS = THICK
LOAD(N) =   890
SPEED(RPM) =   100
CENTRAL OUTER CONTACTS = CENTRAL INNER CONTACTS MULTIPLIED BY 1.08432
MINIMUM OUTER CONTACTS = MINIMUM INNER CONTACTS MULTIPLIED BY 1.10109

                                                                           FILM THICKNESSES ARE IN MICROMETERS

                                                       AFT BEARING, INNER CONTACTS                                          FORWARD BEARING, INNER CONTACTS
TEST                          BASE
TIME PRESSURE TORQUE  SPEED       TEMPA                                                      TEMPF
(HR) (PASCAL)  (N-M)  (RPM)        (C)   BHCAI   XCENI   TCENI   BHMAI   XMINI   TMINI        (C)   BHCFI   XCENI   TCENI   BHMFI   XMINI   TMINI
 1728 4.7E-05   .113  32.00       30.0   .066    .145    .152    .059    .137    .132        32.8   .059    .129    .135    .053    .123    .118
 1800 4.5E-05   .134  24.00       26.7   .063    .166    .177    .056    .158    .152        30.0   .054    .142    .152    .048    .137    .132
 1896 3.7E-05   .177  29.00       27.2   .070    .174    .173    .062    .165    .148        29.4   .063    .157    .156    .057    .150    .135
 2040 4.3E-05   .106  20.00       26.7   .055    .134    .177    .049    .128    .152        29.4   .048    .118    .154    .044    .113    .135
 2160 3.7E-05   .099  25.00       26.7   .065    .184    .177    .057    .175    .152        28.3   .060    .170    .164    .053    .163    .141
 2304 3.6E-05   .120  22.00       26.1   .060    .138    .182    .054    .130    .155        27.8   .056    .127    .168    .050    .121    .144
 2400 3.7E-05   .106  26.00       26.1   .068    .135    .182    .061    .127    .155        28.3   .061    .122    .164    .055    .116    .141
 2496 3.5E-05   .092  17.00       26.1   .050    .117    .182    .045    .111    .155        27.8   .046    .108    .168    .042    .109    .144
 2568 4.0E-05   .085  26.00       27.8   .063    .161    .168    .056    .154    .144        28.9   .060    .153    .160    .054    .147    .138
 2648 3.2E-05   .092  20.00       26.1   .056    .134    .182    .050    .127    .155        27.8   .052    .124    .168    .047    .118    .144
 2808 3.3E-05   .092  24.00       26.1   .064    .178    .182    .057    .170    .155        27.8   .059    .164    .168    .053    .158    .144
 2904 2.7E-05   .092  16.00       25.0   .051    .117    .192    .045    .111    .163        26.7   .047    .108    .177    .042    .103    .152
 3048 2.9E-05   .099  21.00       26.7   .057    .124    .177    .051    .117    .152        28.3   .052    .114    .164    .047    .106    .141
 3192 2.9E-05   .106  22.00       26.7   .059    .101    .177    .053    .094    .152        28.9   .053    .091    .160    .048    .085    .138
 3336 2.8E-05   .099  22.00       27.2   .057    .109    .173    .051    .103    .148        28.3   .054    .104    .164    .049    .098    .141
 3576 2.4E-05   .127  25.00       26.7   .066    .134    .177    .059    .126    .152        28.9   .060    .120    .160    .054    .114    .138
 3816 2.9E-05   .092  21.00       27.2   .055    .304    .173    .050    .297    .148        28.9   .051    .282    .160    .046    .276    .138
 3912 2.6E-05   .106  22.00       26.7   .059    .101    .177    .053    .094    .152        28.9   .053    .091    .160    .048    .085    .138
 4056 2.7E-05   .099  15.00       27.2   .043    .127    .173    .039    .122    .149        29.4   .039    .115    .156    .036    .111    .135
 4200 2.4E-05   .085  15.00       27.2   .043    .121    .173    .039    .116    .148        28.9   .040    .112    .160    .037    .108    .138
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ENDURANCE TEST NO.   2
OIL =  APIEZON A     +ANTI +LEAD NAPH
BEARING ROUGHNESS =   STD
INITIAL OIL FILM THICKNESS = THICK
LOAD(LB) =  200
SPEED(RPM) =   100
CENTRAL OUTER CONTACTS = CENTRAL INNER CONTACTS MULTIPLIED BY 1.08432
MINIMUM OUTER CONTACTS = MINIMUM INNER CONTACTS MULTIPLIED BY 1.10109

                                                              FILM THICKNESSES ARE IN MICROINCHES

                                         AFT BEARING, INNER CONTACTS                                    FORWARD BEARING, INNER CONTACTS
TEST                           BASE
TIME PRESSURE  TORQUE    SPEED      TEMPA                                                  TEMPF
(HR)   (TORR)(OZ-IN)    (RPM)       (F)   BHCAI  XCENI  TCENI  BHMAI  XMINI  TMINI        (F)   BHCFI  XCENI  TCENI  HMMFI  XMINI  TMINI
   0 1.0E-06  42.00   24.00        77.0   2.67   3.72   7.58   2.37   3.91   6.43        77.0   2.67   3.72   7.58   2.37   3.91   6.43
   2 1.0E-06  27.00   28.00        78.0   2.91   4.29   7.37   2.57   3.99   6.27        79.0   2.83   4.18   7.18   2.51   3.85   6.12
   6 1.2E-06  29.00   15.00        81.0   1.70   2.57   6.80   1.54   2.41   5.83        84.0   1.58   2.38   6.29   1.44   2.24   5.42
  24 1.5E-06  13.00   21.00        83.0   2.21   3.53   6.46   1.98   3.30   5.55        87.0   2.00   3.19   5.84   1.81   3.01   5.06
  30 1.2E-06  24.00   30.00        83.0   2.68   4.12   6.46   2.39   3.81   5.55        87.0   2.42   3.73   5.84   2.18   3.47   5.06
  48 1.2E-06  19.00   21.00        82.0   2.12   3.01   6.63   1.91   2.78   5.69        86.0   1.92   2.72   5.98   1.74   2.53   5.18
  76 1.1E-06  25.00   18.00        82.0   1.90   3.11   6.63   1.71   2.91   5.69        86.0   1.71   2.81   5.98   1.56   2.65   5.18
 144 1.0E-06  24.00   40.00        83.0   3.31   5.62   6.46   2.92   5.22   5.55        87.0   2.99   5.08   5.84   2.66   4.76   5.06
 168 9.0E-07  22.00   28.00        82.0   2.62   3.64   6.63   2.33   3.33   5.69        88.0   2.25   3.13   5.70   2.03   2.90   4.95
 192 1.2E-06  27.00   26.00        84.0   2.35   4.25   6.29   2.11   3.98   5.42        89.0   2.08   3.76   5.56   1.88   3.55   4.84
 216 9.9E-07  26.00   28.00        85.0   2.42   4.08   6.14   2.17   3.81   5.30        89.0   2.19   3.69   5.56   1.98   3.44   4.84
 240 8.2E-07  21.00   24.00        88.0   2.13   4.25   5.70   1.93   4.03   4.95        93.0   1.89   3.77   5.05   1.73   3.61   4.43
 312 8.2E-07  25.00   30.00        87.0   2.42   4.56   5.84   2.18   4.24   5.06        91.0   2.20   4.11   5.30   1.99   3.88   4.63
 336 1.0E-06  17.00   25.00        83.0   3.04   5.42   6.46   2.72   5.03   5.55        88.0   2.70   4.78   5.70   2.42   4.48   4.95
 360 8.8E-07  18.00   16.00        83.0   3.06   4.72   6.46   2.72   4.35   5.55        87.0   2.77   4.27   5.84   2.48   3.97   5.06
 385 8.8E-07  23.00   30.00        82.0   2.75   5.11   6.63   2.45   4.76   5.69        87.0   2.42   4.50   5.84   2.18   4.24   5.06
 456 7.1E-07  23.00   27.00        82.0   2.55   3.90   6.63   2.27   3.62   5.69        88.0   2.19   3.35   5.70   1.98   3.15   4.95
 480 8.0E-07  19.00   30.00        82.0   2.75   4.85   6.63   2.45   4.53   5.69        86.0   2.48   4.38   5.98   2.23   4.12   5.18
 504 8.0E-07  20.00   19.00        80.0   1.30   3.38   6.99   1.19   3.25   5.97        83.0   1.20   3.13   6.46   1.11   3.03   5.55
 528 7.0E-07  20.00   28.00        79.0   2.83   4.91   7.18   2.51   4.57   6.12        82.0   2.62   4.54   6.63   2.33   4.25   5.69
 552 6.6E-07  21.00   29.00        80.0   2.83   6.80   6.99   2.51   6.44   5.97        84.0   2.55   6.12   6.29   2.28   5.85   5.42
 624 6.5E-07  20.00   39.00        81.0   3.42   7.18   6.80   3.01   6.73   5.83        85.0   3.09   6.48   6.14   2.74   6.13   5.30
 672 6.8E-07  16.00   24.00        81.0   2.40   4.08   6.80   2.15   3.80   5.83        86.0   2.11   3.58   5.98   1.91   3.38   5.18
 720 6.6E-07  19.00   30.00        84.0   2.61   5.48   6.29   2.34   5.18   5.42        88.0   2.37   4.95   5.70   2.13   4.72   4.95
 792 6.3E-07  19.00   32.00        82.0   2.88   4.28   6.63   2.56   3.92   5.69        90.0   2.36   3.50   5.43   2.13   3.26   4.73
 840 5.8E-07  22.00   36.00        81.0   3.23   6.32   6.80   2.85   5.91   5.83        85.0   2.91   5.70   6.14   2.59   5.37   5.30
 888 5.4E-07  15.00   28.00        82.0   2.62   5.56   6.63   2.33   5.23   5.69        88.0   2.25   4.77   5.70   2.03   4.55   4.95
 970 5.4E-07  20.00   40.00        86.0   2.48   5.17   5.98   2.23   4.88   5.18        91.0   2.20   4.58   5.30   1.99   4.36   4.63
1018 6.0E-07  26.00   41.00        83.0   2.75   5.88   6.46   2.45   5.54   5.55        88.0   2.42   5.19   5.70   2.18   4.94   4.95
1066 5.0E-07  20.00   34.00        82.0   3.02   6.15   6.63   2.67   5.77   5.69        87.0   2.66   5.42   5.84   2.38   5.13   5.06
1138 5.0E-07  14.00   19.00        80.0   2.08   6.16   6.99   1.87   5.91   5.97        84.0   1.87   5.55   6.29   1.70   5.37   5.42
1186 5.8E-07  20.00   19.00        79.0   2.13   5.89   7.18   1.91   5.63   6.12        83.0   1.56   5.30   6.46   1.74   5.11   5.55
1234 5.0E-07  19.00   22.00        84.0   2.08   5.84   6.29   1.88   5.58   5.42        88.0   1.89   5.29   5.70   1.71   5.09   4.95
1306 5.0E-07  21.00   25.00        82.0   2.91   6.61   6.53   2.15   6.28   5.69        88.0   2.07   5.68   5.70   1.87   5.46   4.95
1354 4.0E-07  14.00   25.00        86.0   2.18   6.30   5.98   1.96   6.04   5.14        91.0   1.93   5.57   5.30   1.75   5.40   4.63
1402 4.5E-07  16.00   25.00        90.0   1.97   5.09   5.43   1.79   4.87   4.73        95.0   1.75   4.53   4.83   1.61   4.37   4.25
1448 4.5E-07  17.00   20.00        95.0   1.99   5.61   4.83   1.38   5.92   4.25       100.0   1.33   5.02   4.37   1.24   4.89   3.83
1560 4.0E-07  17.00   24.00        96.0   2.11   5.01   5.98   1.91   4.77   5.18        91.0   1.87   4.44   5.30   1.70   4.26   4.63
1632 4.6E-07  12.00   29.00        85.0   2.49   6.28   6.19   2.23   5.97   5.30        90.0   2.20   5.56   5.43   1.99   5.33   4.73
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ENDURANCE TEST NO.   2
OIL =  APIEZON A    +ANTI +LEAD NAPH
BEARING ROUGHNESS =   STD
INITIAL OIL FILM THICKNESS = THICK
LOAD(LB) =  200
SPEED(RPM) =   100
CENTRAL OUTER CONTACTS = CENTRAL INNER CONTACTS MULTIPLIED BY 1.08432
MINIMUM OUTER CONTACTS = MINIMUM INNER CONTACTS MULTIPLIED BY 1.10109

                                                                      FILM THICKNESSES ARE IN MICROINCHES

                                                   AFT BEARING, INNER CONTACTS                                        FORWARD BEARING, INNER CONTACTS
TEST                          BASE
TIME PRESSURE TORQUE   SPEED      TEMPA                                                            TEMPF
(HR)    (TORR)(OZ-IN)   (RPM)        (F)   HMCAI   XCENI   TCENI   HMMAI   XMINI   TMINI            (F)   HMCFI   XCENI   TCENI   HMMFI   XMINI   TMINI
 1729 1.5E-07   16.00   12.00       86.0    2.60    5.72    5.98    2.33    5.41    5.18           91.0    2.31    5.06    5.40    2.09    4.84    4.63
 1880 1.9E-07   19.00   24.00       80.0    2.46    6.55    6.99    2.20    6.20    5.97           66.0    2.11    5.61    5.98    1.91    5.38    5.18
 1996 2.8E-07   25.00   24.00       81.0    2.76    6.39    6.80    2.45    6.49    5.83           85.0    2.49    6.17    6.14    2.23    5.91    5.30
 2040 1.2E-07   15.00   20.00       80.0    2.16    5.29    6.99    1.93    5.03    5.97           85.0    1.90    4.65    6.14    1.72    4.47    5.30
 2160 2.5E-07   16.00   25.00       80.0    2.54    7.25    6.99    2.26    6.89    5.97           83.0    2.35    6.70    6.46    2.10    6.41    5.55
 2304 2.3E-07   17.00   22.00       79.0    2.38    5.43    7.18    2.12    5.19    6.12           82.0    2.19    5.02    6.63    1.97    4.78    5.69
 2400 2.8E-07   15.00   26.00       79.0    2.68    5.33    7.18    2.38    5.01    6.12           83.0    2.42    4.80    6.46    2.16    4.55    5.55
 2496 2.6E-07   13.00   17.00       79.0    1.97    4.60    7.18    1.77    4.36    6.12           82.0    1.82    4.24    6.63    1.65    4.05    5.69
 2568 1.0E-07   12.00   26.00       82.0    2.48    6.36    6.63    2.21    6.05    5.69           84.0    2.35    6.04    6.29    2.11    5.77    5.42
 2648 2.4E-07   13.00   20.00       79.0    2.22    5.27    7.18    1.98    5.00    6.12           82.0    2.05    4.87    6.63    1.84    4.65    5.69
 2808 2.5E-07   13.00   24.00       79.0    2.53    7.00    7.18    2.25    6.69    6.12           82.0    2.34    6.47    6.63    2.09    6.22    5.69
 2904 2.0E-07   13.00   16.00       77.0    1.99    4.62    7.58    1.78    4.37    6.43           80.0    1.83    4.26    6.99    1.65    4.06    5.97
 3048 2.2E-07   14.00   21.00       80.0    2.24    4.86    6.99    2.00    4.59    5.97           83.0    2.07    4.50    6.46    1.86    4.27    5.55
 3192 2.2E-07   15.00   22.00       80.0    2.31    3.97    6.99    2.07    3.70    5.97           84.0    2.08    3.58    6.29    1.88    3.37    5.42
 3316 2.1E-07   16.00   22.00       81.0    2.25    4.29    6.80    2.02    4.04    5.83           83.0    2.14    4.08    6.46    1.92    3.85    5.55
 3576 1.8E-07   18.00   26.00       80.0    2.61    5.26    6.99    2.32    4.95    5.97           84.0    2.35    4.74    6.29    2.11    4.50    5.42
 3816 2.2E-07   13.00   21.00       81.0    2.18   11.98    6.80    1.95   11.68    5.83           84.0    2.01   11.09    6.29    1.82   10.86    5.42
 3912 1.5E-07   15.00   22.00       80.0    2.31    3.97    6.99    2.07    3.70    5.97           84.0    2.08    3.58    6.29    1.88    3.37    5.42
 4056 2.0E-07   14.00   15.00       81.0    1.70    5.01    6.80    1.54    4.82    5.83           85.0    1.54    4.52    6.14    1.40    4.32    5.30
 4200 1.8E-07   12.00   15.00       81.0    1.70    4.76    6.80    1.54    4.56    5.83           84.0    1.58    4.40    6.29    1.44    4.25    5.42
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ENDURANCE TEST NO.   3
OIL = RHRC 36233
BEARING ROUGHNESS = ROUGH
INITIAL OIL FILM THICKNESS = THICK
LOAD(N) =   890
SPEED(RPM) =   100
CENTRAL OUTER CONTACTS = CENTRAL INNER CONTACTS MULTIPLIED BY 1.08432
MINIMUM OUTER CONTACTS = MINIMUM INNER CONTACTS MULTIPLIED BY 1.10109

                                                                  FILM THICKNESSES ARE IN MICROMETERS

                                                  AFT BEARING, INNER CONTACTS                                 FORWARD BEARING, INNER CONTACTS
TEST                          BASE
TIME PRESSURE TORQUE   SPEED       TEMPA                                                 TEMPF
(HR) (PASCAL)  (N-M)   (RPM)        (C)   BHCAI  XCENI  TCENI  BHMAI  XMINI  TMINI       (C)   BHCFI  XCFNI  TCENI  BHMFI  XMINI  TMINI
   0 1.2E-04   .539   16.00        25.0   .137   .326   .523   .119   .307   .430       25.0   .137   .326   .523   .119   .307   .430
   4 1.1E-04   .339   16.00        28.9   .119   .242   .435   .100   .226   .360       31.7   .101   .213   .383   .088   .201   .319
   8 1.6E-04   .268   22.00        32.2   .124   .232   .379   .108   .215   .312       35.0   .110   .206   .332   .096   .191   .278
  25 2.1E-04   .212   22.00        37.2   .100   .185   .303   .088   .172   .254       40.0   .090   .165   .271   .079   .154   .229
  32 1.6E-04   .198   19.00        37.2   .090   .206   .303   .080   .194   .254       40.0   .081   .184   .271   .071   .174   .229
  48 1.5E-04   .162   20.00        36.1   .098   .171   .317   .086   .159   .266       38.4   .087   .153   .283   .077   .142   .238
  76 1.4E-04   .212   16.00        35.6   .085   .159   .325   .075   .148   .272       38.9   .074   .139   .283   .066   .136   .238
 144 1.3E-04   .205   24.00        34.4   .120   .233   .340   .105   .216   .284       37.2   .107   .207   .303   .094   .194   .254
 168 1.2E-04   .219   22.00        35.0   .110   .246   .332   .096   .232   .278       38.3   .096   .215   .290   .084   .203   .244
 192 1.6E-04   .177   17.00        36.1   .087   .185   .317   .077   .174   .266       40.0   .074   .158   .271   .066   .150   .229
 216 1.1E-04   .191   22.00        35.6   .107   .211   .325   .094   .197   .272       39.4   .092   .180   .277   .081   .169   .233
 288 1.2E-04   .205   26.00        35.0   .124   .324   .332   .108   .305   .278       36.7   .116   .302   .310   .101   .285   .260
 312 1.1E-04   .205   22.00        37.2   .100   .257   .303   .088   .243   .254       40.6   .088   .225   .265   .078   .214   .224
 336 1.4E-04   .205   19.00        35.0   .099   .261   .332   .087   .248   .278       38.3   .086   .228   .290   .076   .217   .244
 360 1.2E-04   .169   22.00        35.0   .110   .214   .332   .096   .199   .278       38.9   .094   .182   .283   .083   .171   .238
 385 1.2E-04   .191   24.00        35.0   .135   .273   .332   .117   .253   .278       38.9   .115   .233   .283   .100   .217   .238
 456 4.5E-05   .219   26.00        33.9   .127   .275   .348   .110   .257   .291       37.2   .110   .239   .303   .096   .225   .254
 480 1.1E-04   .219   20.00        33.9   .108   .270   .348   .094   .255   .291       37.2   .094   .235   .303   .082   .223   .254
 504 1.1E-04   .198   14.00        33.3   .085   .229   .357   .075   .217   .297       37.2   .072   .195   .303   .064   .186   .254
 528 9.4E-05   .205   29.00        33.3   .144   .295   .357   .125   .273   .297       37.2   .123   .250   .303   .107   .234   .254
 552 4.4E-05   .191   24.00        33.9   .123   .285   .348   .107   .268   .291       37.2   .107   .248   .303   .094   .235   .254
 624 4.7E-05   .240   24.00        33.3   .126   .293   .357   .110   .275   .297       37.2   .107   .249   .303   .094   .235   .254
 672 9.1E-05   .212   22.00        33.9   .115   .254   .348   .101   .238   .291       37.8   .098   .216   .296   .086   .204   .249
 720 4.8E-05   .169   21.00        34.4   .109   .257   .340   .095   .242   .284       37.8   .095   .224   .296   .083   .212   .249
 792 8.4E-05   .226   19.00        35.0   .099   .241   .332   .087   .228   .278       38.3   .086   .210   .290   .076   .200   .244
 840 7.7E-05   .184   17.00        35.0   .091   .236   .332   .080   .224   .278       37.2   .083   .216   .303   .074   .205   .254
 864 7.5E-05   .162   13.00        37.2   .068   .177   .303   .061   .168   .254       43.9   .053   .137   .234   .048   .131   .198
 936 7.2E-05   .177   19.00        36.7   .092   .190   .310   .081   .178   .260       40.6   .079   .163   .265   .070   .154   .224
1010 8.0E-05   .169   13.00        34.4   .077   .227   .340   .068   .216   .284       38.3   .065   .193   .290   .058   .186   .244
1066 6.7E-05   .205   14.00        33.3   .085   .249   .357   .075   .237   .297       37.2   .072   .212   .303   .064   .203   .254
1138 6.7E-05   .311   22.00        28.9   .144   .361   .435   .125   .340   .360       32.2   .124   .311   .374   .108   .294   .312
1186 7.7E-05   .205   20.00        29.4   .131   .311   .424   .114   .292   .351       33.3   .110   .262   .357   .096   .247   .297
1214 6.7E-05   .374   19.00        27.8   .136   .472   .458   .118   .451   .378       27.8   .136   .472   .458   .118   .451   .378
1306 6.7E-05   .219   22.00        31.1   .130   .277   .393   .113   .259   .327       33.9   .115   .246   .349   .101   .230   .291
1354 5.3E-05   .177   10.00        33.9   .065   .250   .348   .058   .241   .291       37.2   .056   .217   .303   .051   .211   .254
1402 6.0E-05   .177   16.00        36.1   .083   .287   .317   .074   .275   .266       40.0   .071   .245   .271   .063   .237   .229
1488 6.0E-05   .177   17.00        38.9   .078   .230   .283   .069   .219   .238       42.8   .067   .198   .244   .060   .190   .206
1546 5.1E-05   .205   14.00        35.6   .077   .241   .325   .069   .231   .272       39.4   .066   .206   .277   .059   .198   .233
1632 4.8E-05   .177   22.00        36.7   .103   .239   .310   .090   .225   .260       40.0   .090   .209   .271   .079   .198   .229
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ENDURANCE TEST NO.   3
OIL = NARC 36233
BEARING ROUGHNESS = ROUGH
INITIAL OIL FILM THICKNESS = THICK
LOAD(N) =   690
SPEED(RPM) =    100
CENTRAL OUTER CONTACTS = CENTRAL INNER CONTACTS MULTIPLIED BY 1.08432
MINIMUM OUTER CONTACTS = MINIMUM INNER CONTACTS MULTIPLIED BY 1.10109

                                                          FILM THICKNESSES ARE IN MICROMETERS

                                         AFT BEARING, INNER CONTACTS                              FORWARD BEARING, INNER CONTACTS
TEST                      BASE
TIME PRESSURE TORQUE     SPEED      TEMPA                                               TEMPF
(HR) (PASCAL)  (N-M)     (RPM)       (C)  BHCAI  XCENI  TCENI  BHMAI  XMINI  TMINI       (C)  BHCFI  XCENI  TCENI  BHMFI  XMINI  TMINI
 1728 4.7E-05   .141     22.00      35.0   .110   .236   .332   .096   .222   .278      37.8   .098   .211   .296   .086   .199   .249
 1900 4.5E-05   .148     15.00      32.8   .091   .240   .365   .081   .228   .304      36.1   .079   .208   .317   .070   .199   .266
 1996 3.7E-05   .148     22.00      32.8   .121   .259   .365   .105   .243   .304      36.7   .103   .220   .310   .090   .207   .260
 2040 4.3E-05   .177     19.00      31.7   .091   .245   .383   .081   .232   .319      35.6   .077   .207   .325   .069   .197   .272
 2160 3.7E-05   .191     16.00      31.1   .103   .291   .393   .091   .277   .327      35.0   .087   .246   .332   .077   .235   .278
 2304 3.4E-05   .191     12.00      31.1   .084   .256   .393   .074   .244   .327      34.4   .072   .221   .340   .064   .212   .284
 2400 3.7E-05   .205     11.00      31.1   .078   .234   .393   .070   .223   .327      35.6   .065   .193   .325   .058   .185   .272
 2496 3.5E-05   .205     17.00      31.1   .108   .280   .393   .094   .265   .327      34.4   .093   .242   .340   .082   .236   .284
 2568 4.0E-05   .148     22.00      31.1   .130   .255   .393   .113   .237   .327      35.0   .110   .215   .332   .096   .201   .278
 2664 3.2E-05   .177     19.00      31.1   .117   .217   .393   .102   .201   .327      35.6   .097   .179   .325   .085   .167   .272
 2808 3.7E-05   .198     20.00      31.1   .121   .295   .393   .106   .277   .327      35.0   .103   .249   .332   .090   .236   .278
 2904 2.7E-05   .205     28.00      29.4   .167   .357   .424   .144   .332   .351      33.9   .137   .294   .348   .119   .275   .291
 3048 2.9E-05   .184     14.00      31.1   .094   .267   .393   .092   .254   .327      35.0   .079   .225   .332   .070   .216   .278
 3192 2.9E-05   .191     24.00      29.4   .149   .365   .424   .129   .341   .351      33.3   .126   .307   .357   .110   .289   .297
 3336 2.8E-05   .194     25.00      31.1   .143   .280   .393   .124   .259   .327      34.4   .124   .242   .340   .108   .225   .284
 3576 2.4E-05   .177     28.00      40.0   .107   .222   .271   .094   .207   .229      43.9   .092   .191   .234   .081   .180   .148
 3816 2.9E-05   .240     32.00      30.6   .175   .341   .403   .151   .314   .335      34.4   .148   .287   .340   .128   .267   .284
 3912 2.0E-05   .226     29.00      30.0   .167   .312   .413   .144   .287   .343      33.9   .141   .263   .348   .122   .244   .291
 4056 2.7E-05   .339     33.00      31.1   .175   .270   .393   .150   .245   .327      35.0   .148   .229   .332   .128   .208   .278
 4200 2.4E-05   .367     35.00      30.0   .192   .273   .413   .164   .244   .343      33.9   .162   .230   .348   .139   .207   .291
 4392 1.7E-05   .169     30.00      31.7   .159   .282   .383   .137   .259   .319      35.0   .138   .244   .332   .120   .225   .278
 4536 2.7E-05   .275     23.00      28.9   .149   .350   .435   .129   .328   .360      33.3   .122   .287   .357   .106   .271   .297
 4584 3.3E-05   .325     27.00      31.7   .147   .279   .383   .128   .258   .319      35.0   .128   .242   .332   .111   .225   .278
 4704 1.4E-05   .226     44.00      31.1   .216   .330   .393   .184   .297   .327      34.4   .187   .286   .340   .160   .259   .284
 4824 1.3E-05   .240     25.00      31.1   .143   .362   .393   .124   .341   .327      34.4   .124   .313   .340   .108   .297   .284
 4896 1.4E-05   .233     26.00      27.8   .171   .406   .458   .147   .380   .378      31.7   .143   .340   .383   .124   .321   .319
 5016 1.9E-05   .212     45.00      30.0   .192   .364   .413   .164   .334   .343      33.3   .166   .314   .357   .143   .290   .297
 5088 1.9E-05   .241     27.00      30.0   .159   .308   .413   .137   .284   .343      33.3   .137   .266   .357   .119   .247   .297
 5184 1.9E-05   .169     23.00      31.7   .131   .302   .383   .114   .284   .319      35.0   .114   .262   .332   .099   .248   .278
 5256 1.6E-05   .212     27.00      31.1   .151   .323   .393   .131   .301   .327      34.4   .131   .280   .340   .114   .262   .284
 5328 2.0E-05   .184     24.00      28.9   .172   .363   .435   .148   .336   .360      33.3   .141   .297   .357   .122   .277   .297
 5424 1.6E-05   .226     24.00      29.4   .149   .324   .424   .129   .301   .351      33.3   .126   .272   .357   .110   .255   .297
 5520 1.6E-05   .254     16.00      30.0   .108   .369   .413   .095   .352   .343      33.3   .094   .319   .357   .082   .306   .297
 5592 1.6E-05   .248     23.00      30.6   .138   .373   .403   .120   .353   .335      33.3   .122   .330   .357   .106   .314   .297
 5664 1.6E-05   .226     25.00      30.0   .150   .313   .413   .130   .291   .343      33.3   .130   .270   .357   .113   .253   .297
 5688 9.3E-06   .177     39.00      29.4   .213   .360   .424   .182   .328   .351      32.2   .188   .318   .374   .161   .291   .312
 5832 5.6E-06   .127     23.00      30.6   .138   .273   .403   .120   .254   .335      33.3   .122   .242   .357   .106   .226   .297
 5928 5.3E-06   .155     26.00      30.0   .155   .302   .413   .133   .279   .343      32.8   .137   .267   .365   .119   .248   .304
 6070 4.4E-06   .155     23.00      30.0   .141   .289   .413   .122   .268   .343      32.8   .125   .255   .365   .109   .238   .304
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ENDURANCE TEST NO.   3
OIL = RMMC 36233
BEARING ROUGHNESS = ROUGH
INITIAL OIL FILM THICKNESS = THICK
LOAD(N) =   890
SPEED(RPM) =    100
CENTRAL OUTER CONTACTS = CENTRAL INNER CONTACTS MULTIPLIED BY 1.08432
MINIMUM OUTER CONTACTS = MINIMUM INNER CONTACTS MULTIPLIED BY 1.10109


                                                              FILM THICKNESSES ARE IN MICROMETERS

                                          AFT BEARING, INNER CONTACTS                                  FORWARD BEARING, INNER CONTACTS
TEST                      BASE
TIME PRESSURE TORQUE   SPEED      TEMPA                                                     TEMPF
(HR) (PASCAL)  (N-M)   (RPM)        (C)  HMCAI  XCENI  TCENI  HMMAI  XMINI  TMINI          (C)  HMCFI  XCENI  TCENI  HMMFI  XMINI  TMINI
 6096 4.7E-06   .127   25.00       27.8   .166   .337   .458   .143   .311   .378         30.6   .146   .296   .403   .127   .276   .335
 6168 4.7E-06   .127   24.00       30.0   .146   .303   .413   .126   .282   .343         33.3   .126   .262   .357   .110   .245   .297
 6264 4.7E-06   .155   24.00       30.0   .146   .273   .413   .126   .253   .343         32.8   .129   .242   .365   .112   .224   .309
 6360 4.0E-06   .141   26.00       29.4   .158   .295   .424   .137   .271   .351         32.2   .140   .260   .374   .121   .241   .312
 6432 4.0E-06   .141   30.00       29.4   .176   .306   .424   .151   .281   .351         33.3   .148   .258   .357   .128   .238   .297
 6528 4.0E-06   .177   35.00       29.4   .197   .333   .424   .168   .303   .351         32.2   .174   .299   .374   .149   .269   .312
 6600 4.0E-06   .155   22.00       30.0   .137   .274   .413   .119   .255   .343         33.3   .118   .237   .357   .103   .221   .297
 6720 4.0E-06   .148   26.00       28.9   .163   .313   .435   .140   .288   .360         31.7   .143   .276   .383   .124   .256   .319
 6768 4.0E-06   .106   25.00       29.4   .154   .299   .424   .133   .277   .351         31.7   .139   .271   .383   .121   .252   .319
 6840 4.0E-06   .162   26.00       32.8   .137   .261   .365   .119   .241   .304         30.7   .116   .222   .310   .101   .206   .260
 6936 4.0E-06   .120   23.00       30.6   .138   .231   .403   .120   .212   .335         33.3   .122   .205   .357   .106   .189   .297
 7032 4.7E-06   .092   26.00       31.1   .147   .315   .393   .127   .293   .327         33.3   .133   .286   .357   .116   .267   .297
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ENDURANCE TEST NO.   3
OIL = PARC 36233
BEARING ROUGHNESS = ROUGH
INITIAL OIL FILM THICKNESS = THICK
LOAD(LB) =  200
SPEED(RPM) =    100
CENTRAL OUTER CONTACTS = CENTRAL INNER CONTACTS MULTIPLIED BY 1.08432
MINIMUM OUTER CONTACTS = MINIMUM INNER CONTACTS MULTIPLIED BY 1.10109

                                                     FILM THICKNESSES ARE IN MICROINCHES

                                     AFT BEARING, INNER CONTACTS                                FORWARD BEARING, INNER CONTACTS
TEST                       CASE
TIME PRESSURE TORQUE      SPEED      TEMPA                                                  TEMP,
(HR)    (TORR)(OZ-IN)     (RPM)        (F)   BHCAI  XCENI  TCENI  BHMAI  XMINI  TMINI         (F)   BHCFI  XCENI  TCENI  BHMFI  XMINI  TMINI
   0 9.3E-07  25.00     16.00         77.0   5.40  12.84  20.57   4.69  12.09  16.91        77.0   5.40  12.84  20.57   4.69  12.09  16.91
   4 1.0E-06  48.00     16.00         84.0   4.49   9.51  17.11   3.93   8.91  14.17        89.0   3.96   8.39  15.10   3.48   7.90  12.56
   8 1.2E-06  38.00     22.00         98.0   4.88   9.12  14.73   4.25   8.45  12.27        95.0   4.33   8.09  13.08   3.79   7.53  10.94
  25 1.6E-06  30.00     22.00         99.0   3.95   7.28  11.93   3.47   6.76  10.01       104.0   3.53   6.51  10.67   3.12   6.08   9.00
  32 1.2E-06  21.00     19.00         99.0   3.55   8.10  11.93   3.13   7.64  10.01       104.0   3.18   7.25  10.67   2.81   6.87   9.00
  48 1.2E-06  23.00     20.00         97.0   3.86   6.74  12.48   3.39   6.25  10.46       102.0   3.44   6.02  11.15   3.04   5.61   9.39
  76 1.0E-06  30.00     16.00         96.0   3.35   6.27  12.78   2.97   5.85  10.70       102.0   2.93   5.48  11.15   2.60   5.13   9.39
 144 1.0E-06  29.00     24.00         94.0   4.72   9.16  13.39   4.12   8.51  11.19        99.0   4.21   8.16  11.93   3.69   7.62  10.01
 168 9.0E-07  31.00     22.00         95.0   4.33   9.70  13.08   3.79   9.12  10.94       101.0   3.78   8.46  11.40   3.32   8.00   9.59
 192 1.2E-06  25.00     17.00         97.0   3.92   7.28  12.48   3.43   6.84  10.46       104.0   2.93   6.23  10.67   2.60   5.89   9.00
 216 9.9E-07  27.00     22.00         96.0   4.23   8.31  12.78   3.71   7.77  10.70       103.0   3.61   7.10  10.91   3.18   6.66   9.19
 288 4.7E-07  29.00     26.00         95.0   4.89  12.74  13.08   4.26  12.01  10.94        98.0   4.56  11.89  12.20   3.99  11.24  10.23
 312 8.2E-07  29.00     22.00         99.0   3.95  10.10  11.93   3.47   9.58  10.01       105.0   3.46   8.85  10.45   3.05   8.43   8.81
 336 1.0E-06  29.00     19.00         95.0   3.89  10.28  13.08   3.42   9.77  10.94       101.0   3.39   8.96  11.40   3.00   8.56   9.59
 360 8.4E-07  24.00     22.00         95.0   4.33   8.41  13.08   3.79   7.83  10.94       102.0   3.69   7.17  11.15   3.25   6.72   9.39
 385 9.8E-07  27.00     29.00         95.0   5.30  10.75  13.08   4.60   9.97  10.94       102.0   4.52   9.17  11.15   3.95   8.56   9.39
 456 7.1E-07  31.00     25.00         93.0   4.98  10.82  13.71   4.34  10.14  11.44        99.0   4.34   9.42  11.93   3.79   8.67  10.01
 480 8.0E-07  31.00     20.00         93.0   4.23  10.62  13.71   3.71  10.06  11.44        99.0   3.68   9.24  11.93   3.24   8.60  10.01
 504 8.9E-07  28.00     14.00         92.0   3.34   9.03  14.04   2.96   8.56  11.71        99.0   2.84   7.67  11.93   2.53   7.32  10.01
 528 7.0E-07  29.00     29.00         92.0   5.69  11.60  14.04   4.97  10.76  11.71        99.0   4.83   9.86  11.93   4.21   9.20  10.01
 552 6.6E-07  27.00     24.00         93.0   4.84  11.22  13.71   4.21  10.56  11.44        99.0   4.21   9.77  11.93   3.69   9.24  10.01
 624 6.5E-07  34.00     24.00         92.0   4.95  11.54  14.04   4.31  10.82  11.71        99.0   4.21   9.80  11.93   3.69   9.25  10.01
 672 6.8E-07  30.00     22.00         93.0   4.59   9.99  13.71   3.97   9.38  11.44       100.0   3.86   8.50  11.66   3.39   8.03   9.80
 720 6.6E-07  24.00     21.00         94.0   4.28  10.12  13.39   3.75   9.51  11.19       100.0   3.73   8.82  11.66   3.29   8.33   9.80
 792 6.6E-07  32.00     19.00         95.0   3.89   9.50  13.08   3.42   8.99  10.94       101.0   3.39   8.28  11.40   3.00   7.86   9.59
 840 5.8E-07  26.00     17.00         95.0   3.59   9.31  13.08   3.16   8.81  10.94        99.0   3.27   8.49  11.93   2.90   8.06  10.01
 888 5.6E-07  23.00     13.00         99.0   2.69   6.97  11.93   2.40   6.60  10.01       111.0   2.08   5.38   9.20   1.87   5.14   7.80
 936 5.4E-07  25.00     19.00         98.0   3.63   7.49  12.20   3.20   7.02  10.23       105.0   3.11   6.41  10.45   2.76   6.04   8.81
1018 6.0E-07  24.00     13.00         94.0   3.02   8.94  13.39   2.68   8.52  11.19       101.0   2.57   7.61  11.40   2.30   7.30   9.59
1066 5.0E-07  29.00     14.00         92.0   3.34   9.81  14.04   2.96   9.34  11.71        99.0   2.84   8.33  11.93   2.53   7.99  10.01
1138 5.0E-07  44.00     22.00         84.0   5.67  14.22  17.11   4.91  13.38  14.17        90.0   4.88  12.24  14.73   4.25  11.59  12.27
1186 5.8E-07  29.00     20.00         85.0   5.15  12.24  16.68   4.48  11.49  13.82        92.0   4.34  10.30  14.04   3.80   9.74  11.71
1234 5.0E-07  53.00     19.00         82.0   5.36  18.60  18.02   4.65  17.74  14.89        82.0   5.36  18.60  18.02   4.65  17.74  14.89
1306 5.0E-07  31.00     22.00         88.0   5.12  10.92  15.47   4.46  10.18  12.86        93.0   4.54   9.68  13.71   3.97   9.06  11.44
1354 4.4E-07  25.00     16.00         93.0   2.55   9.84  13.71   2.28   9.49  11.44        99.0   2.22   8.56  11.93   2.00   8.30  10.01
1402 4.5E-07  25.00     16.00         97.0   3.28  11.28  12.48   2.90  10.83  10.46       104.0   2.80   9.65  10.67   2.49   9.32   9.00
1488 4.5E-07  25.00     17.00        102.0   3.06   9.06  11.15   2.72   8.63   9.39       109.0   2.63   7.79   9.59   2.35   7.47   8.12
1560 4.4E-07  29.00     14.00         96.0   3.04   9.51  12.78   2.70   9.09  10.70       103.0   2.60   8.12  10.91   2.32   7.81   9.19
1632 3.6E-07  25.00     22.00         98.0   4.04   9.41  12.20   3.55   8.88  10.23       104.0   3.53   8.23  10.67   3.12   7.61   9.00
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ENDURANCE TEST NO. 1
OIL = MARC TW211
BEARING ROUGHNESS = ROUGH
INITIAL OIL FILM THICKNESS = THICK
LOAD(LB) = 200.
SPEED(RPM) = 100
CENTRAL OUTER CONTACTS = CENTRAL INNER CONTACTS MULTIPLIED BY 1.08932
MINIMUM OUTER CONTACTS = MINIMUM INNER CONTACTS MULTIPLIED BY 1.10109

FILM THICKNESSES ARE IN MICROINCHES

TEST TIME (HR)	PRESSURE (TORR)	TORQUE (OZ-IN)	BASE SPEED (RPM)	AFT BEARING, INNER CONTACTS TEMPA (F)	HMCAI	HCENI	TCENI	HMMAI	HMINI	TMINI	FORWARD BEARING, INNER CONTACTS TEMPF (F)	HMCFI	HCENI	TCENI	HMMFI	HMINI	TMINI
1725	1.54E-07	20.00	22.00	94.0	4.33	9.31	13.08	3.74	8.73	10.94	100.0	3.86	8.30	11.66	3.39	7.62	9.80
1800	3.94E-07	20.00	15.00	91.0	3.60	9.44	14.38	3.18	8.98	11.98	97.0	3.13	8.20	12.48	2.77	7.84	10.96
1846	2.85E-07	21.00	22.00	91.0	4.76	10.21	14.38	4.15	9.56	11.98	98.0	4.04	8.66	12.20	3.55	8.17	10.23
2060	3.24E-07	25.00	14.00	89.0	3.59	9.63	15.10	3.17	9.13	12.56	96.0	3.04	8.15	12.78	2.70	7.77	10.70
2160	2.44E-07	23.00	16.00	88.0	4.06	11.46	15.47	3.57	10.84	12.86	95.0	3.43	9.69	13.08	3.03	9.26	10.94
2184	2.34E-07	27.00	12.00	88.0	3.29	10.07	15.47	2.92	9.61	12.86	94.0	2.85	8.71	13.39	2.59	8.36	11.19
2400	2.81E-07	24.00	11.00	88.0	3.04	9.20	15.47	2.79	8.78	12.86	96.0	2.55	7.60	12.78	2.28	7.30	10.70
2496	2.61E-07	24.00	17.00	88.0	4.29	11.02	15.47	3.72	10.42	12.86	94.0	3.67	9.54	13.39	3.24	9.06	11.19
2568	[illegible]	28.00	22.00	84.0	5.12	10.03	15.47	4.46	9.32	12.86	95.0	4.33	8.47	13.08	3.79	7.94	10.94
2688	2.84E-07	25.00	19.00	88.0	4.60	8.53	15.47	4.02	7.90	12.86	96.0	3.80	7.04	12.78	3.34	6.57	10.70
2808	2.54E-07	28.00	26.00	88.0	4.78	11.60	15.47	4.17	10.91	12.86	95.0	4.04	9.80	13.08	3.55	9.28	10.94
2904	2.04E-07	24.04	24.00	85.0	6.59	14.07	16.68	5.67	13.07	13.82	93.0	5.41	11.56	13.71	4.69	10.82	11.44
3048	2.24E-07	26.00	14.00	86.0	3.68	10.50	15.47	3.25	9.94	12.86	95.0	3.11	8.87	13.08	2.76	8.44	10.94
3192	2.24E-07	23.00	24.00	84.0	5.89	14.36	16.68	5.09	13.41	13.82	92.0	4.95	12.09	14.04	4.31	11.36	11.71
3336	2.16E-07	21.00	25.00	88.0	5.62	11.03	15.47	4.87	10.20	12.86	94.0	4.87	9.55	13.39	4.24	8.98	11.19
3576	1.64E-07	26.00	28.00	104.0	4.21	8.73	10.67	3.69	8.16	9.00	111.0	3.63	7.52	9.20	3.20	7.04	7.80
3816	2.24E-07	18.00	12.00	87.0	6.40	13.41	15.66	5.43	12.36	13.17	94.0	5.83	11.32	13.39	5.04	10.50	11.19
3912	1.54E-07	12.70	24.00	84.0	6.59	12.27	16.27	5.67	11.32	13.49	93.0	5.55	10.34	13.71	4.81	9.60	11.44
4056	2.08E-07	48.00	31.00	88.0	6.89	14.65	15.47	5.92	9.64	12.86	95.0	5.82	9.03	13.08	5.04	8.29	10.94
4200	1.83E-07	52.00	15.00	86.0	7.56	10.75	16.27	6.47	9.62	13.49	93.0	6.37	9.06	13.71	5.49	8.16	11.44
4392	1.34E-07	24.00	10.00	89.0	6.27	11.09	15.10	5.41	10.19	12.56	95.0	5.43	9.61	13.08	4.71	8.84	10.94
4536	2.06E-07	34.00	21.00	84.0	5.65	13.76	17.11	5.06	12.91	14.17	92.0	4.80	11.31	14.04	4.19	10.68	11.71
4584	2.54E-07	44.00	23.00	89.0	5.81	10.98	15.10	5.07	10.16	12.56	95.0	5.03	9.51	13.08	4.37	8.85	10.94
4728	5.24E-07	32.00	44.00	88.0	8.50	13.01	15.47	7.29	11.71	12.86	94.0	7.35	11.26	13.39	6.30	10.19	11.19
4824	1.42E-07	16.00	25.00	88.0	5.62	14.26	15.47	4.87	13.43	12.86	94.0	4.87	12.33	13.39	4.24	11.68	11.19
4896	1.25E-07	13.00	26.00	82.0	6.74	16.00	18.02	5.80	14.98	14.89	89.0	5.65	13.41	15.10	4.89	12.64	12.56
5016	1.44E-07	10.00	35.00	84.0	7.56	14.34	16.27	6.47	13.17	13.49	92.0	6.52	12.37	14.04	5.62	11.43	11.71
5088	1.44E-07	17.00	27.40	86.0	6.25	12.13	16.27	5.40	11.20	13.49	92.0	5.40	10.47	14.04	4.68	9.72	11.71
5184	1.44E-07	20.00	21.00	84.0	[illegible]	11.90	15.10	4.99	11.19	12.56	95.0	4.47	10.31	13.06	3.91	9.79	10.94
5256	1.24E-07	10.00	22.00	88.0	5.95	12.73	15.47	5.14	11.84	12.86	94.0	5.15	11.01	13.39	4.47	10.30	11.19
5328	1.54E-07	26.00	29.00	84.0	6.76	14.28	17.11	5.81	13.21	14.17	92.0	5.54	11.71	14.04	4.80	10.92	11.71
5424	1.24E-07	12.00	24.00	85.0	5.89	12.74	16.68	5.09	11.87	13.82	92.0	4.95	10.72	14.04	4.31	10.05	11.71
5520	1.24E-07	16.00	16.00	86.0	4.27	14.54	16.27	3.74	13.86	13.49	92.0	3.68	12.55	14.04	3.25	12.03	11.71
5592	1.24E-07	38.00	21.00	87.0	5.43	14.60	15.86	4.71	13.89	13.17	92.0	4.80	12.94	14.04	4.19	12.35	11.71
5664	1.24E-07	12.00	26.00	84.0	5.91	12.34	16.27	5.11	11.46	13.49	92.0	5.10	10.65	14.04	4.44	9.95	11.71
5684	7.04E-08	25.00	34.00	85.0	8.39	14.19	16.68	7.15	12.41	13.82	90.0	7.41	12.53	14.73	6.34	11.46	12.27
5812	4.24E-08	18.00	21.00	87.0	5.43	10.76	15.46	4.71	10.00	13.17	92.0	4.80	9.52	14.04	4.19	8.69	11.71
5928	4.04E-08	22.00	26.00	86.0	6.08	11.89	16.27	5.24	10.98	13.49	91.0	5.38	10.51	14.33	4.67	9.75	11.98
6000	3.84E-08	22.00	21.00	84.0	5.56	11.36	16.27	4.82	10.54	13.49	91.0	4.92	10.05	14.38	4.28	9.37	11.98

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ENDURANCE TEST NO.   1
OIL = [illegible]
BEARING ROUGHNESS = ROUGH
INITIAL OIL FILM THICKNESS = THICK
LOAD(LB) =  200
SPEED(RPM) =   130
CENTRAL OUTER CONTACTS = CENTRAL INNER CONTACTS MULTIPLIED BY 1.08932
MINIMUM OUTER CONTACTS = MINIMUM INNER CONTACTS MULTIPLIED BY 1.10109

                                                       FILM THICKNESSES ARE IN MICROINCHES

                                         AFT BEARING, INNER CONTACTS                                   FORWARD BEARING, INNER CONTACTS
TEST                           BASE
TIME  PRESSURE  TORQUE        SPEED    TEMPA                                                   TEMPF
(HRS)   ([illegible])(OZ-IN)   (RPM)     (F)   BMCAI  XCENI  TCENI  BMMAI  XMINI  TMINI         (F)   BMCFI  XCENI  TCENI  BMMFI  XMINI  TMINI
 6096  1.5E-08   18.00     25.00     87.0   6.55  14.25  18.02   5.69  12.26  14.89        87.0   5.77  11.66  15.86   4.99  10.85  13.17
 6160  3.5E-08   19.00     20.00     86.0   5.70  11.93  16.27   4.97  11.12  13.49        92.0   4.95  10.30  14.04   4.31   9.65  11.71
 6244  1.5E-08   22.00     20.00     86.0   5.74  10.76  16.27   4.97   9.95  13.49        91.0   5.07   9.51  14.38   4.41   8.84  11.98
 6364  1.4E-08   20.00     26.00     85.0   6.29  11.61  16.68   5.38  10.60  13.82        90.0   5.51  10.25  14.73   4.78   9.47  12.27
 6412  3.0E-08   20.00     18.00     85.0   6.43  12.06  16.68   5.95  11.05  13.82        92.0   5.83  10.15  14.04   5.04   9.36  11.71
 6528  1.4E-08   25.00     16.00     84.0   7.35  13.12  16.68   6.43  11.92  13.82        90.0   6.45  11.59  14.73   5.64  10.56  12.27
 6640  1.9E-08   22.00     22.00     86.0   5.39  10.80  16.27   4.67  10.05  13.49        92.0   4.65   9.32  14.04   4.06   8.72  11.71
 6720  1.4E-08   21.00     24.00     84.0   6.40  12.12  17.11   5.52  11.36  14.17        69.0   5.65  10.87  15.10   4.89  10.07  12.56
 6844  3.0E-08   15.00     25.00     85.0   6.06  11.79  16.68   5.24  10.92  13.82        89.0   5.49  10.67  15.10   4.76   9.92  12.56
 6904  1.4E-08   21.00     26.00     91.0   5.38  10.28  14.32   4.67   9.49  11.90        98.0   4.56   8.77  12.20   3.99   8.10  10.23
 6986  1.4E-08   17.00     23.00     87.0   5.43   9.11  15.86   4.71   8.35  13.17        92.0   4.80   8.06  14.04   4.14   7.42  11.71
 7014  1.5E-08   18.00     26.00     88.0   5.79  12.91  15.47   5.01  11.55  12.86        92.0   5.25  11.26  14.04   4.56  10.52  11.71
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LIST OF REFERENCES

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